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GEOPHYSICAL RECONNAISSANCE AT KAWERAU, NEW ZEALAND

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Summary

Geophysical methods were used to investigate the possibility of exploiting the Onepu hydrothermal resources in the Kawerau papermills. Changes in the hydrology and chemistry of the hot springs in the last fifty years are attributed to downcutting by the Tarawera River into a Recent alluvial fan; surface run-off has given place to seepage and alkaline waters have given place to acid. Electrical surveying extended the known hot-water zone across the Tarawera River, where test holes gave satisfactory steam and water discharges, and exploitation followed. The natural heat flow was estimated at about 25,000 k.cal. per sec. (above 12° C), but the potential output of eight drillholes at 100 lb per sq. in. pressure is 2·7 times this figure. High enthalpy discharges and enthalpies which rise with the wellhead pressure may result from tapping the margin of the hot-water zone.

Seismic refraction tests showed the existence of extensive rhyolites, which, being less permeable than the pumice sediments, act as cap rocks in the hydrothermal system. These rhyolites have little influence on the magnetic field intensity, having low remanent polarization. A gravity survey reveals some details of the geological structure and suggests a genetic relationship between the hot water and rhyolitic intrusions, and between faulting and the volcanic cone of Mt Edgecumbe.

INTRODUCTION

Kawerau and the Onepu hot springs lie close to the Tarawera River, about twelve miles from its outflow into the Bay of Plenty, and about five miles south-west of the township of Te Teko (Fig. 1). Onepu is one of New Zealand's smaller hydrothermal areas, but it is among the

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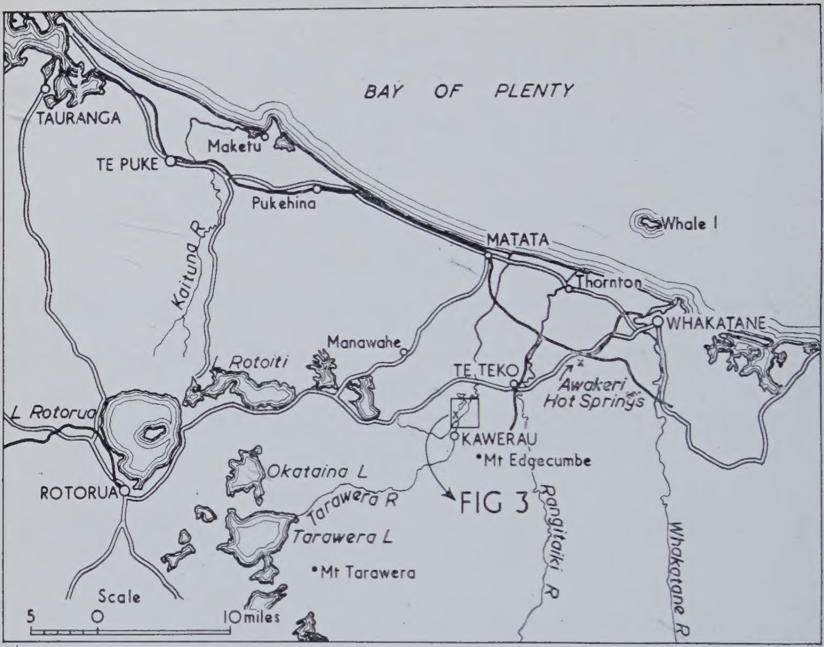

Fig. 1.—Locality map, Western Bay of Plenty district.

most interesting, for it shows very clearly the influence of fluctuations of the water table upon the character of the hot springs.

The area is one in which the Tarawera and Rangitaiki rivers debouch from narrow valleys on to flood plains extending to the coast. This is flourishing farm country, but it is close to the northern fringe of the Kaingaroa Forest plantations of *Pinus radiata*. Kawerau was the abode of the Tuwharetoa Maoris before they migrated to the Taupo region (Best, 1925), and Umupokapoka (a part of the Onepu hydrothermal area) is mentioned in early versions of the Maori legend describing the travels of Ngatoroirangi and the origin of New Zealand's geysers and volcanoes (Locke, 1882).

Little detailed information has been published on this area. Herbert (1921) gives the Onepu waters a brief mention, and Grange (1937) deals with the geology of adjacent territory, quoting an analysis of a Ruruanga spring. Macpherson (1944) described the geology and hot springs in a brief paper, giving his impression that the Onepu hydrothermal area was one of the more active of the whole country. Modriniak (1945) has described earlier geophysical work connected with the Awakeri hot springs, about nine miles to the north-east; these are bicarbonate springs; test drilling failed to locate temperatures higher than those at surface.

Surveys of the Onepu springs and of the surrounding country were made by the Geophysical Survey Branch of the Geophysics Division, Department of Scientific and Industrial Research to examine the possibility of future utilization of the hydrothermal resources. The work is described as a reconnaissance because no attempt was made at complete investigation of scientific problems, the intention being merely to outline the main features. This was followed by test drilling by the Ministry of Works Geothermal Investigations Group, and finally by drilling of production holes for the Tasman Pulp and Paper Company, Ltd. Certain aspects of this subsequent work are dealt with below. A report (unpublished)* on the geophysical survey was prepared in 1952, but the scientific aspects of the work may now be reassessed in the light of geothermal investigations at Wairakei (Grange, 1955; Banwell, *et al.,* 1957; Studt, 1957; Gregg, 1958).

GEOLOGY AND STRUCTURE

Like Wairakei, Kawerau lies on the main Quaternary volcanic belt of the North Island; it is on a straight line between the two volcanoes Tarawera and White Island, and is less than two miles from the geologically Recent cone of Mount Edgecumbe.

The only published geological map is that of Macpherson (1944), upon which Fig. 2 is based, but the following brief resumé of the geology owes much to personal communications from officers of the Geological Survey, notably Messrs J. Healy and A. C. Beck.

Geology

The basement rocks are Mesozoic greywacke and argillite; highly contorted and in places silicified, they outcrop in the ranges south of Awakeri and Whakatane. Coarse greywacke gravels appear at Matata, but the nearest exposure of the parent rock in the west is at Pukehina, eight miles further up the coast.

In coastal sections, the basement is overlain by undated marine sandstones and gravels; inland by rhyolitic pumice breccias. The breccias are loosely consolidated, and on either side of the Tarawera River they form a series of accordant hilltops, warped into a gentle trough, plunging below the alluvial plains to the north. Close to Onepu this accordance is broken by upstanding exposures of older compacted pumice sandstone, and south of Mount Edgecumbe the breccia sequence is broken by an owharoite sheet. Owharoite (Grange, 1934) is a welded, rhyolitic pumice tuff or ignimbrite, characterized by lenses of obsidian. It forms prominent cliffs in the Tarawera and Rangitaiki valleys. In the west the breccias abut the Manawahe rhyolite.

The alluvial plains are made up of pumice, quartz, and rhyolite sands and gravels, with occasional muds and hydrothermally altered clays.

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*Report on Geothermal Investigations at Te Teko, by F. E. Studt. (Report on open file at Geophysics Division, D.S.I.R.).

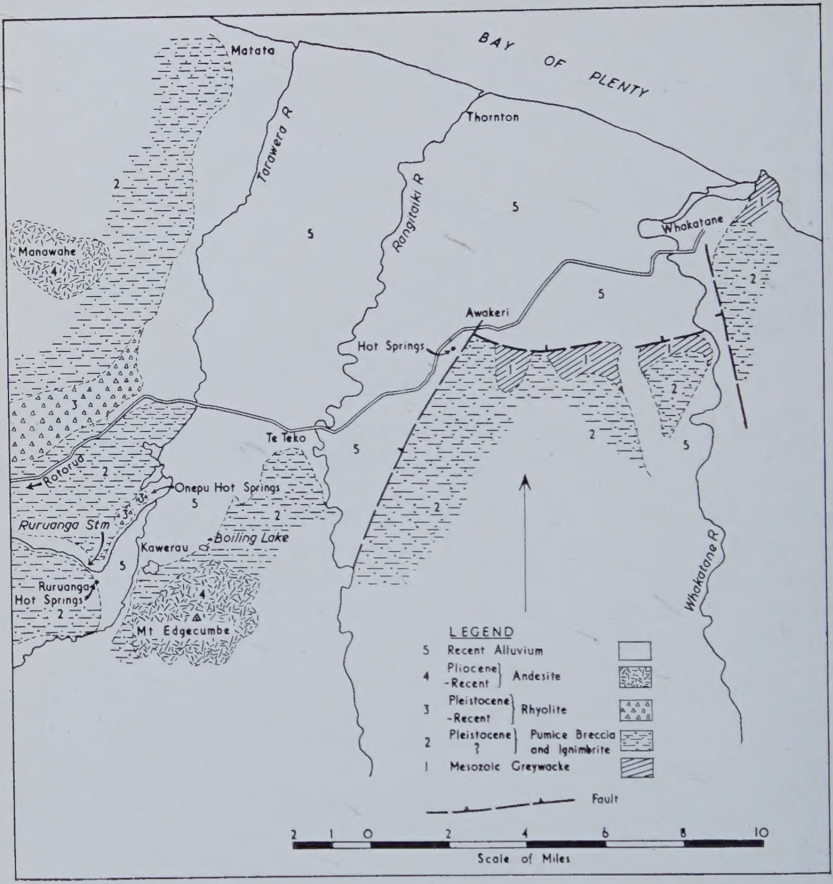

FIG. 2.—Geology of the Kawerau district.

The whole area is covered with Recent volcanic ash, the youngest member being a basaltic lapilli bed, deposited during the 1886 eruption of Mount Tarawera, about twenty miles to the south.

The andesite cone of Mount Edgecumbe (Putauaki), rising nearly 3,000 ft above the plains, has several small craters at its summit, and a single satellite dome on its south-west slopes. The andesite flows appear to overlie the earliest ash beds; they are therefore much younger than the Manawahe andesite, which Grange assumed to be Pliocene. Two small domes adjacent to the hot springs at Onepu are of rhyolitic composition, and in places have suffered extensive hydrothermal alteration. Drillholes and seismic surveys have shown that rhyolite flows and breccias underlie much of the alluvium around

Kawerau; they are themselves underlain by earlier pumiceous sediments. There are upwards of 1,000 ft of rhyolites on the east bank of the Tarawera River; they thicken (to nearly 1,500 ft) and rise in the direction of the rhyolite domes, suggesting a common origin for both.

Structure

Macpherson (1944, p. 69) regarded the country between the Tarawera and Rangitaiki rivers as the northern extension of the Rotorua-Taupo Graben (Grange, 1937, pp. 46-48). He further described the country between Whakatane and Awakeri as a sunken area east of the graben proper. In fact, there is no simple graben here, for the Mesozoic rocks in the east appear in a stepwise distribution of fault blocks, each with north-south elongation, but each extending farther north than its western neighbour, so that the whole has the general north-north-east trend of the graben farther south. One such block forms the Whakatane Range; a second extends south from the cross fault at Awakeri, and, as will be seen later, gravity data indicate a third block terminating at Mount Edgecumbe, though this does not outcrop in the Kawerau neighbourhood.

The graben is also complicated in the west by the extensive rhyolites about Manawahe. Both Grange and Macpherson accepted these as the western margin of the graben, but gravity data suggest that the true margin may be farther west.

Kawerau is thus situated in a large structural depression which is continuous with the main depression throughout the Central North Island volcanic belt. The geological structure and its relation to the hot springs are discussed in greater detail in connection with the Kawerau gravity survey.

History of the Tarawera River

This history has an important bearing on certain aspects of the hot springs.

Macpherson pointed out that although the Tarawera and Rangitaiki rivers are aggrading their lower flood plains, they are entrenched 30 to 40 ft into the flats a few miles from the sea; from this he deduced a quite recent uplift. However, the warping of the accordant breccia surface is due to subsidence; the tributary drainage is ponded, which is not a sign of uplift, and although there has been obvious recession of the sea, this is due to rapid progradation with volcanic debris. The entrenchment of the rivers is due to downcutting into a recent alluvial fan, composed of volcanic debris from the Tarawera country to the south.

The present rate of erosion of this fan by the Tarawera River is visibly great, and a study of successive topographic surveys shows that there has been rapid drainage of marginal ponded areas in the last few decades. Farmers living alongside the river have estimated the rate of downcutting close to Kawerau at 10 ft in the last 30 years; they have good cause to know this figure, for it has removed from Kawerau the danger of repeated flooding which formerly occurred. The rapid erosion is important to the farmers of the Matata country also, for deposition of the load is likely to lead to increasingly frequent flooding in the lower reaches of the river.

Downcutting at such a rate cannot have been long-lived, particularly as it is still active at the foot of the fan. It may have begun after the 1886 eruption of Mount Tarawera, but was probably resuscitated in 1904, following a breakout from Lake Tarawera which caused silting-up along the river (Maclaren, 1906). The fan itself is much older than 1886, for it is everywhere covered by the Tarawera basalt lapilli. The earlier Kaharoa eruption (Grange, 1931), from the same vicinity, may have contributed much of the alluvium; radiocarbon dating gives 930 ± 70 years as the (corrected) age of material from this eruption (Fergusson and Rafter, 1955, 1957). No doubt there were other such events.

Successive surveys, dated 1860, 1922, and 1954, have been compared by Mr R. L. Roud of Rotorua. During this period there has been rapid migration of meanders except close to the hot springs, where the river appears to have been fixed by silicification in the banks. There is, nevertheless, a recent course along the west margin of the valley, which was tributary to the Rangitaiki River.

HYDROTHERMAL ACTIVITY

Onepu hot springs are situated on the left bank of the Tarawera River, close to the southern tip of the small Lake Rotoitipaku; Fig. 3 shows the location of the more important features. The active area here covers little more than $\frac{1}{4}$ sq. mile, but hot-water seepages and scattered hot pools extend up the Tarawera River and Ruruanga Stream for about a mile above their confluence. Farther south, where the Ruruanga Stream enters the Tarawera Valley, is the site of the Ruruanga Springs (Grange, 1937). Another area of minor activity, including the so-called Boiling Lake, appears among the marshes on the opposite side of the Tarawera Valley, two miles east of Onepu.

In all, the present surface activity covers only about $\frac{1}{2}$ sq. mile. Electrical prospecting and test drilling have shown that hot water underlies a rather larger area, and outcrops of leached and silicified rocks suggest that the hydrothermal activity was formerly more extensive than it is today. Even with these extensions, Onepu remains much smaller than many of New Zealand's better known hydrothermal areas; nevertheless, it is one of the most interesting, owing to the changes which have accompanied the rise and fall of the Tarawera River.

An early report (Colonial Laboratory, 1904) mentions one Onepu spring "on the north side of the Lakelet Umupokapoka" yielding 300,000 gal. (per day). This is nearly twice the present surface discharge from all Onepu hot springs together, and neither spring nor lakelet could be located by Macpherson. It is probable that both have disappeared with the receding water table; the former position of Umupokapoka is almost certainly now marked by a dry sintered lake bed (Fig. 3) with sinter terraces at the north end deposited by the former spring. Stagnant hot pools among these terraces are now several feet below surface.

Silica sinter is as a rule built up only by voluminous flows of very hot water, and the thickness of the terrace thus suggests a long active life for the springs. Water level must therefore have been higher than at present for considerable periods. This would have been possible only during aggradational phases of the river's history, so that the alluvial fan and the sinter are probably contemporaneous. It is of course possible that these changes in the hydrothermal features mark a real diminution in the heat supply during the last half-century, but the rapidity with which the changes have taken place suggests a more superficial cause, such as lowering of the water table.

Chemistry of the Hot Springs

A natural corollary of the recession of the water table is a recent trend towards acidity in the Onepu spring waters. In both 1904 and 1922 the waters were classed as alkaline (Col. Lab., 1904; Dom. Lab., 1922); but of 14 spring waters examined in the present work (Table 1) only four were found to be alkaline, and all but one of these were very small springs. The one large alkaline spring is obviously a new feature; having appeared close to water level in the bank of the Tarawera River shortly before the survey commenced, it began to erode rapidly back through the scrub. Nine of the sampled waters were acid, three strongly so. It would be impossible today to justify the labelling of Onepu waters generally as alkaline.

As at Wairakei, however, drillhole samples increase in alkalinity with depth. Acidity is, in fact, a superficial feature, due to oxidation of the hydrogen sulphide content of the water. Kaplan (1956) has argued that such oxidation may be partly atmospheric and partly bacteriological, but both processes would depend on the depth of the water table, which controls the volume of discharge and rate of runoff, and therefore the time during which the sulphide is susceptible to oxidation.

The scarcity of mud pools at Onepu is a sign that the transition is a recent feature, for acid conditions cannot have existed long enough for the waters to attack and break down the surrounding rocks. Also, Table 1 shows no samples with very low chloride content, such as are found in other acid hydrothermal areas. A low chloride content is

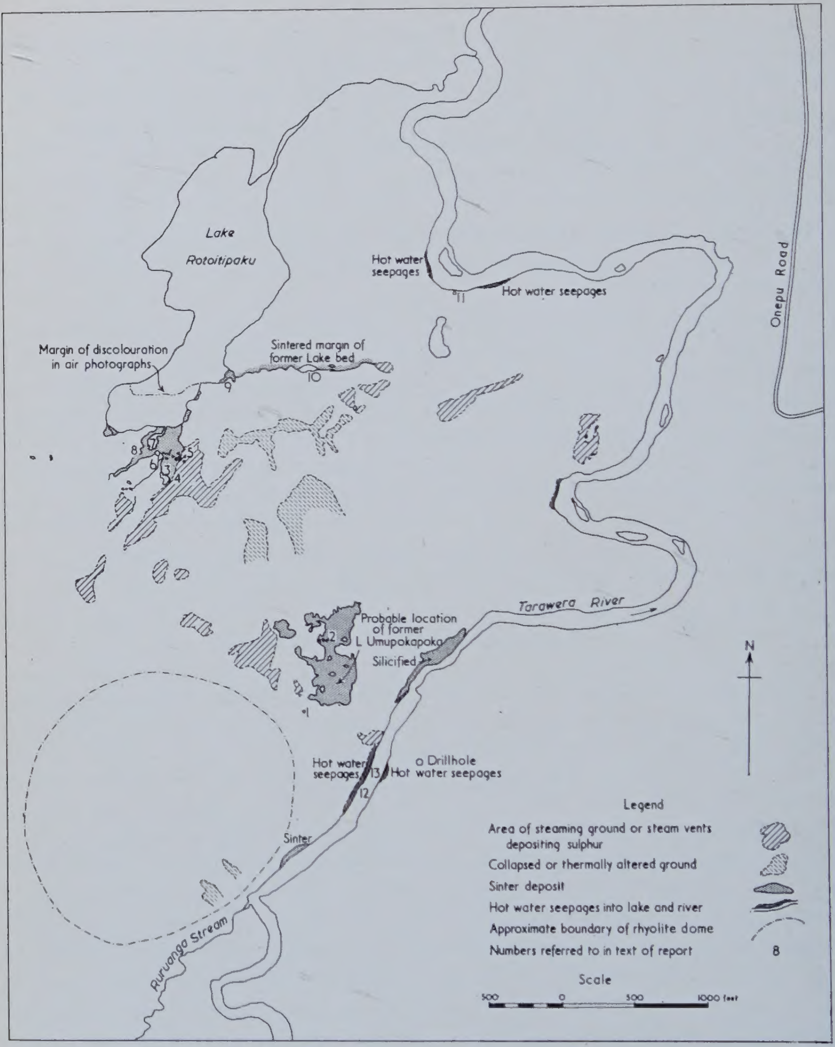
Lake
Rotoitipaku
Hot water seepages
11
Hot water seepages
Onepu Road
Margin of discolouration in air photographs
Sintered margin of former Lake bed
9
10
8
7
6
5
3
4
Tarawera River
Probable location of former L. Umupokapoka
2
Silicified
1
N
Hot water seepages
13
o Drillhole
Hot water seepages
12
Sinter
Ruruanga Stream
Legend
Area of steaming ground or steam vents depositing sulphur
Collapsed or thermally altered ground
Sinter deposit
Hot water seepages into lake and river
Approximate boundary of rhyolite dome
Numbers referred to in text of report
8
Scale
500
0
500
1000 feet

FIG. 3.—Onepu hydrothermal area.

generally taken to indicate ground water which has been heated by steam (Grange, 1955, pp. 28-29). Absence of such waters indicates either that there is no steam-heated ground water, or that there has as yet been insufficient time for the chloride to be lost from such waters.

The whole range in chloride content of the Onepu samples is small by comparison with Wairakei—300 to 600 parts per million, compared with 0 to over 2,000 p.p.m. At Wairakei it has been argued (Studt,

Table 1.—Some Characteristics of Onepu Waters.

Sample No.	Temperature (° C)	pH	Chloride content (p.p.m.)	Conductivity $(\Omega^{-1}\text{cm}^{-1}) \times 10^{-5}$	Remarks
1	68	2·8	305	176	Cloudy, no discharge.
2	72	6·3	422	156	Clear bubbling pool, small discharge. Probable location of former lakelet Umupokapoka; sintered lake bed; sinter terraces at N.W. margin with entrenched pools and mudpots.
3	94	7·2	539	182	Small clear spring discharging into ponded area.
4	99·5	7·5	572	184	As 3.
5	63	2·2	370	400	Small, cloudy, yellow bubbling pool, typical of several nearby.
6	82	7·0	510	170	8 ft pool at foot of grey sinter terrace.
7	86	6·4	490	165	S.W. margin of hot lakelet adjoining Rotoitipaku. Dark scum on surface, little gas. Temperature, 91° C at 30 ft depth.
7a	90	6·3	480	165	West margin of 7.
8	75	3·2	310	155	Small pool, numerous gas seeps, sulphur deposit on bottom. Discharge about 5 gal/min.
9	85	6·3	350	125	Several small clear springs discharging into Rotoitipaku.
10	95·5	7·6	425	145	Representative of small pools entrenched in sintered margin of former lake.
11	100·5	8·2	360	135	Clear, discharge about 50 gal/min. Rapidly eroding back through scrub from river's edge.
12	92	6·7	370	135	Typical clear hot water seepage in river bank.
13	87	5·3	390	145	As 12.
16	16	7·2	50	30	Tarawera River, one mile upstream from confluence with Ruruanga.
17	18	7·2	55	30	Tarawera River, Rotorua highway, 1 mile downstream from active area.
D.S.I.R. drillhole N77/1. Depth of sample (ft) in column 1.					
52	103·5	7·1	48	30	
100	122·5	7·2	119	51	
165	148·5	7·6	532	169	

For the location of these springs see Fig. 3.

Chloride content expressed in parts per million.

Conductivity measured at room temperature (18° C).

Tawera River water was circulated in hole N77/1 while drilling.

1957) that a high chloride range is a result of shortage of ground water; this leads on the one hand to boiling, when the steam fraction and the steam-heated ground water carry no chlorides, and on the other to recirculation of hydrothermal water to make good the deficiency of ground water, which results in gradual accumulation of chlorides in the hydrothermal system. At Onepu, these processes would be reduced to a minimum, because the small extent of the area, the proximity of the Tarawera River, and the extreme permeability of the unconsolidated alluvium all combine to ensure ready access of ground water. It is significant that the extreme chloride figures occur in the springs most remote from the river, and are related to temperature and alkalinity as at Wairakei; whereas springs bordering the river have similar chloride content (about 370 p.p.m.) irrespective of temperature and alkalinity.

Minor Hydrothermal Areas

The relation to Onepu of the Ruruanga and Boiling Lake areas is uncertain. An analysis for one acid spring at Ruruanga is given by Grange (1937, p. 103); it shows low chloride content, sulphate being the main acid radical. These springs have since degenerated with the recession of the water table into a number of quietly steaming vents, which become stagnant hot pools only when the nearby stream floods in winter.

The Boiling Lake is so called because of the violent agitation of its waters by gas bubbles. It is probably identical with the "Lake Waimangeao, near Patauaki, Mt. Edgecumbe", mentioned by Skey (1878), which frequently caused the deaths of birds attempting to fly across it, owing to the carbon dioxide evolved from its waters. There are innumerable small gas seeps in the surrounding marsh country, but there is little heat flow to surface. Water sampling has shown weak acidity and low conductivity, a combination suggesting that the bicarbonate ion is here predominant.

Both these minor areas might be fed by gas and steam from Onepu, separating and migrating beneath an impermeable cover in much the same way as has been postulated for the sulphate and bicarbonate areas at Wairakei (Grange, 1955). Some connection between Onepu and Ruruanga seems not unlikely, in view of the scattered hot ground and hydrothermal alteration between the two. There is, however, little evidence for a connection between Onepu and the Boiling Lake.

HEAT FLOW

The heat flow at Onepu is not easy to assess, since much of it takes place through the beds of the Tarawera River and Lake Rotoitipaku. Even at the most active points, the southern tip of Rotoitipaku and the northern margin of the former Umupokapoka, remarkably little water is discharged at surface. The total discharge is estimated to be only about 9 litres per sec. (120 gal. per min.) at an estimated mean temperature of 90° C. This represents a heat loss of 700 k.cal. per sec. above 12° C. (12° C is the average ambient ground-water temperature.)

There are at least 56,000 square metres (14 acres) of steaming ground, including numerous steam vents with temperatures up to 100° C. No measurements of heat loss were made, 40 cal. per sq. metre per sec. being selected as a mean figure, based on measurements made by Healy and Banwell at Wairakei (Banwell, *et al.*, 1957). Banwell showed that in steaming ground the thermal gradient disappears at quite small depths, with the temperature close to boiling point, so that conduction plays a very small part in the heat loss; disappearance of the thermal gradient also implies that the impedance to steam rising from water table to surface is not a material factor. The depth to water table should not therefore affect this figure. Heat loss from steaming ground thus amounts to about 2,000 k.cal. per sec.

An attempt to measure heat flow in seepage to the Tarawera River was made by temperature measurements in the river above and below the hot area, but since the temperature rise is very small, no great accuracy can be claimed for the result. Fluctuating rates of evaporation, radiation, and insolation made the actual observed temperature rise quite variable, and a correction was therefore derived by simultaneous observation of sections of the river up- and down-stream from the hot area. To minimise the disturbing influences, measurements were made under overcast skies with high humidity. A mean rise of 0·8° C in the 21,300 litres/sec. flow of the Tarawera River (750 cusecs) represents a heat flow of about 17,000 k.cal. per sec. above river temperature, or 18,000 k.cal. per sec. above 12° C.

Voluminous upflow of hot water into Lake Rotoitipaku can be seen at one or two points, but the heat flow cannot be assessed by the method used in the river because practically all the heat is lost by evaporation in the lake. A rough estimate, based on a few marginal temperatures, using curves published by Banwell, *et al.* (1957), suggests that the evaporative heat loss is probably not greater than 3,000 k.cal. per sec. Of this flow perhaps 10% has been accounted for already in nearby springs discharging into the lake.

For the conductive heat loss in the Wairakei region, Gregg (1958) assumed a mean thermal gradient of 1° C per foot and a soil conductivity of 10^{-3} cal./cm. sec. ° C. Benseman, in more recent measurements, uses 3×10^{-3} as a more appropriate value for the conductivity (pers. comm.). Using this latter figure, the conductive heat loss over ½ sq. mile of country becomes 1,200 k.cal. per sec. The above thermal gradient may be considered rather high for the Onepu area itself, but on the other hand several drillholes in apparently cold areas surrounding Onepu have shown much higher gradients than would be expected in cold areas; these undoubtedly contribute to the conductive heat loss.

It is believed, therefore, that the total Onepu heat flow is of the order of 25,000 k.cal. per sec. (about 100 theoretical megawatts) reckoned above 12° C. This is less than one-fifth of the total heat flow at Wairakei (Grange, 1955, p. 50), but rather more than that of the Geyser Valley alone, which is of comparable size. The heat flow per unit area is probably higher than at Wairakei, owing to the much smaller contribution of steaming ground to the Onepu total. Macpherson was quite justified, therefore, in his impression that this is one of the more active areas, despite the fact that a high proportion of the heat flow is not immediately apparent.

ELECTRICAL SURVEY

Since the Tarawera Plain east of the river offers a more suitable site for large industrial plant than does Onepu itself, it was desirable to prospect for possible extensions of the hot water in this direction. An electrical resistivity survey of the plain was therefore made, using the Wenner system, with four equally spaced electrodes in line, and commutated D.C. power supply.

The resistivity of a rock formation decreases with increase of temperature and with increase in salinity of the interstitial water, so that it is possible to map a hydrothermal area by resistivity observations. A good example of such work in Iceland is described by Bödvarsson (1950). There are two complications, however. In the first place, the resistivity is also related to the porosity of the rocks—in fact, porosity mapping is the chief application of resistivity surveying. The porosity of some of the Kawerau swamp areas is sufficient to give quite low resistivity near to the surface. This is no handicap where the swamp can be recognized as such, but where it has been covered by alluvium, confusion may arise. In the second place, saline water could have a wider distribution than hot water, but as a rule the reverse is found in New Zealand's hydrothermal areas. Since the electrical survey alone is unable to discriminate between the various causes of low resistivity, it is sometimes of value in a negative, rather than in a positive sense. That is to say, an area in which resistivity is high may confidently be labelled cold, whereas one in which resistivity is low may or may not be hot.

A number of initial tests were made in known hot and cold areas with progressively expanding electrode spread, the purpose of which is to give increasing current penetration and thus explore the distribution of resistivity with depth. Under these conditions, the resistivity is given by $\rho = 2\pi a(V/I)$, where a is the electrode spacing, I the current applied to the outer electrodes, and V the potential measured between the inner electrodes. Some of the results are shown in Fig. 4, observed resistivity being plotted against electrode spacing. These curves, which are discussed in greater detail below, fall naturally into three groups: those in which there is a sharp drop in resistivity, usually followed by a rise (curves 1-4), represent hot conditions; those in which there is a more gradual fall (5-7) represent cold conditions; curve 8, with low initial values and little decline with increased spacing, represents the swampy country. The best contrast between hot and cold country is recorded with an electrode separation of just under 100 ft; at this spacing, the mean values in hot and cold country were approximately 60 and 600 ohm-metres respectively, the minimum contrast between any two curves being about 2½ to 1. A value of 150 ohm-metres may be taken as an approximate dividing line between hot and cold water.

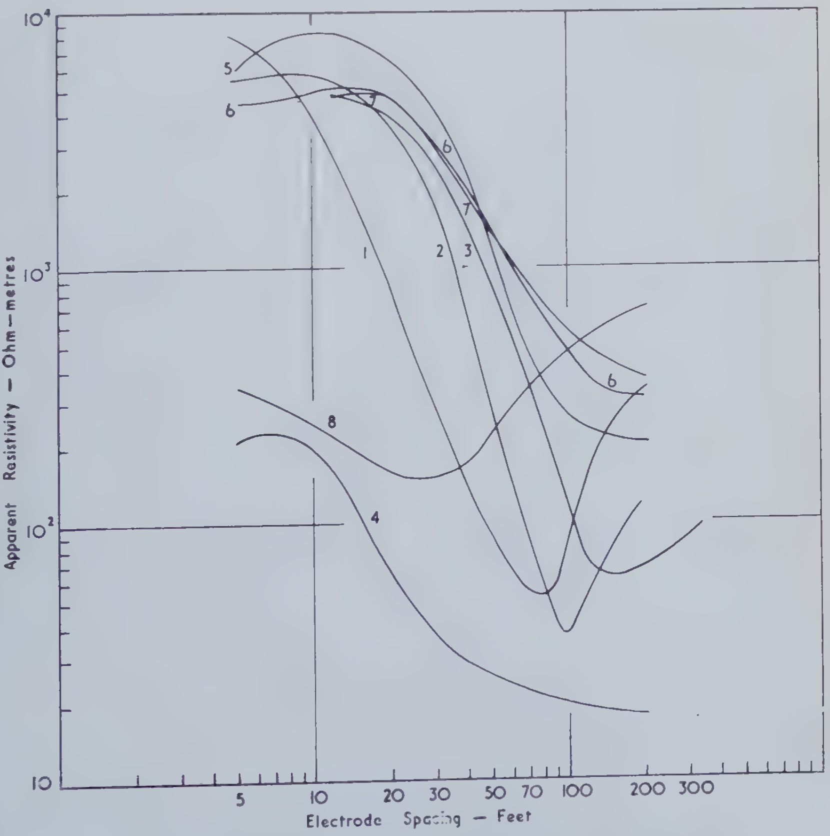

FIG. 4.—Resistivity tests, with expanding electrode spread, in hot (1–4) and cold areas (5–8).

Using 100 ft electrode spacing, therefore, 14 miles of traverse were run, with observations at 200 ft intervals. The results of this work are shown in Fig. 5 in the form of iso-resistivity contours. Owing to rather wide fluctuations in observed resistivity between adjacent stations (due to near-surface inhomogeneities), it has been necessary to take three-point running means in order to draw these contours.

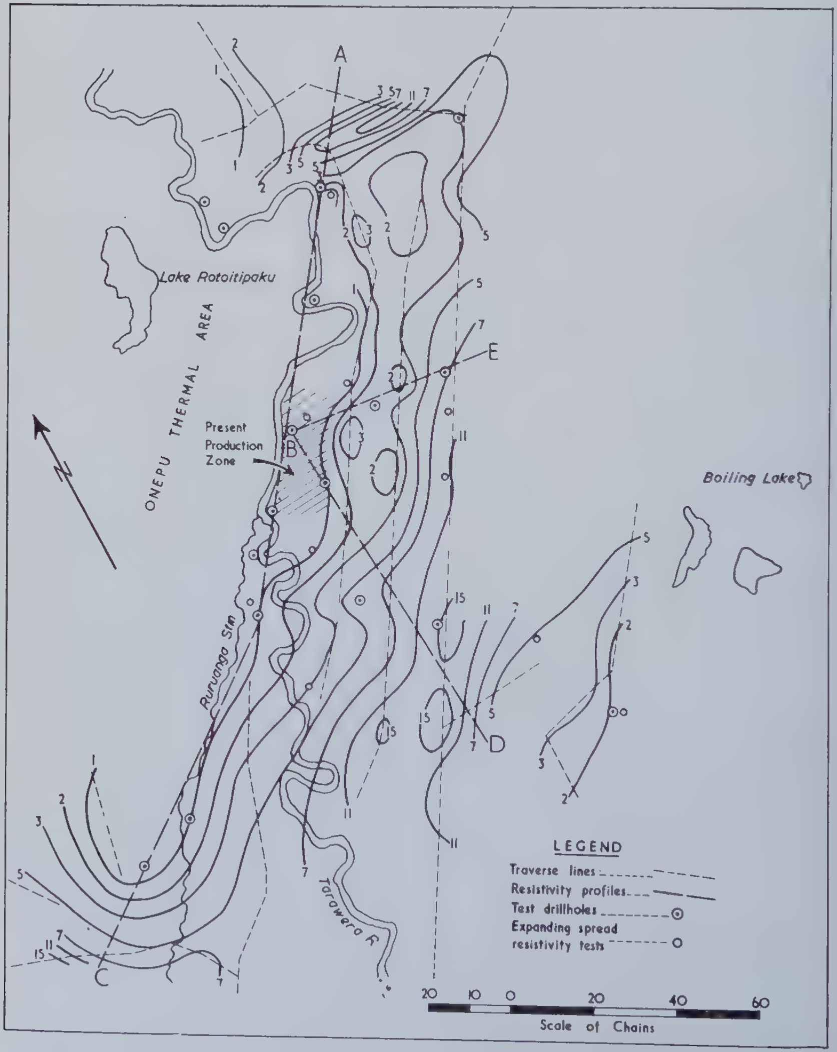

FIG. 5.—Resistivity survey of the Kawerau Plain.

It is seen that, except in the north, the active Onepu area is ringed by the resistivity contours in such a way that hot conditions at shallow depth cannot extend far to the east of the Tarawera River, but that there is a substantial tract of country along the immediate east bank in which hot water may be present. Of this there was no visible evidence whatsoever, beyond a single small hot-water seepage at the water line in the river bank, but confirmation was obtained in a number of shallow exploratory drillholes in which temperatures were measured, and seven 2,000 ft holes are now drawing steam and hot water from this area. Moreover, a further hole drilled close to the proposed mill site, where the resistivity is about 250 ohm-metres, failed to find exploitable temperatures. Fig. 6 compares isotherms based on drillhole temperatures with the resistivity data along three profiles.

In the north, as also in the Boiling Lake area, drillhole temperatures rise slowly, if at all, and water samples have shown low mineral content. The low resistivity must therefore be due to high porosity, and wood brought up in core samples from drillholes suggests that buried swamp beds are present here. A further interesting feature in the north is the anomalous belt of high resistivity running eastward from the sharp bend in the Tarawera River. This probably marks a buried extension of the spur of compact pumice sandstone, around which the bend in the river is cut, for this material appears much less porous than the overlying alluvium and pumice breccia.

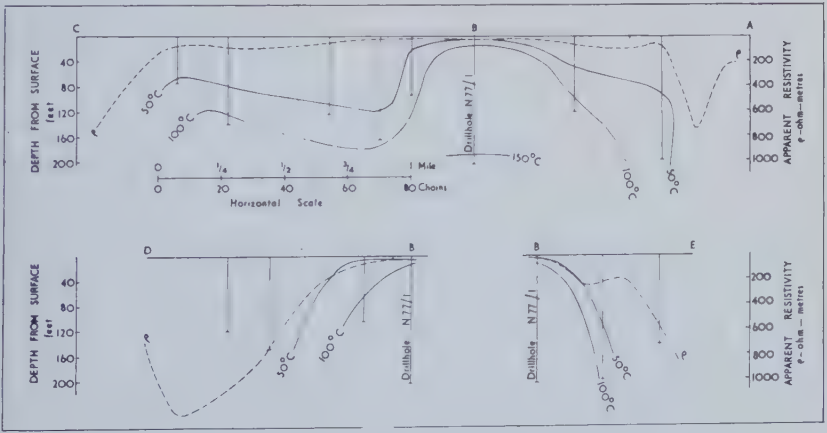

FIG. 6.—Comparison of resistivity curves with isotherms.

Discussion

Detailed analysis of the initial test data was made by the methods of Pirson and Roman, wherein the field curve is matched to a family of standard curves, the displacement of the axes yielding values of true resistivity and thickness for successive layers of rock. The assumption of discrete layers of differing resistivity is not always satisfactory in hydrothermal work, where the temperature is known to increase more or less continuously with depth, but for present purposes this approximation is acceptable since there are well defined layers.

The resistivity of the surface alluvium is 5,000 ohm-metres or more in all parts except swamps, and very active areas where evaporation and condensation take place above the water table. As is to be expected, the soil resistivity is usually rather less than that of the parent alluvium. At the water table (10-20 ft deep) the resistivity drops abruptly to several hundred ohm-metres in cold country, and to several tens of ohm-metres in hot. The subsequent rise in the graphs for hot country indicates a layer of several hundred ohm-metres at a depth of 100 to 200 ft. This probably corresponds with the silicified layers which are found at and above the top of the rhyolite.

With one exception, the measured conductivity of the Onepeu waters ranges from 125 to 184 × 10^{-5} reciprocal ohm-cm at room temperature, which is equivalent to a resistivity of about 5 to 8 ohm-metres at room temperature, or $1\frac{1}{2}$ to $2\frac{1}{2}$ ohm-metres at 100° C. This corresponds to the resistivity of a solution containing 900 to 400 p.p.m. of chloride as NaCl, and is commensurate with actual chloride figures (600 to 300 p.p.m.) since sulphate and other ions also contribute to the conductivity of the spring waters. The porosity of the unconsolidated alluvium is likely to be 25 to 30%; reference to a curve published by Heiland (1946, page 636) shows that, with this porosity, the ratio of formation resistivity to water resistivity is between 6:1 and 8:1, so that the figure for alluvium carrying hot water would be about 10 to 20 ohm-metres. Values of this order were measured close to the hot springs (e.g. curve 4, Fig. 4), but they rise steadily away from the active area.

A resistivity survey with fixed spread yields only values of overall resistivity for the whole current path, that is to say they include the near-surface layers, which introduce a smoothing effect. However, this smoothing is more serious when the surface layers are highly conducting than in the present case, where they are highly resistive; the lack of a very abrupt change at the margin of the active area therefore reflects the actual conditions in the ground.

The reduction in porosity due to silicification above the rhyolite in hot country is such as to make the resistivity at this depth very similar to that in the cold country, and the values in the near-surface layers are also similar, so that the details of the survey relate almost entirely to the ground between the water table and the silicified horizon. This is important, because the distribution of hot water at this depth may be quite different from that at greater depths, especially if there are impermeable layers causing lateral movement of the hot water on its way to the surface. The deeper hot water could, of course, be mapped by utilizing a very much larger electrode spread to obtain greater current penetration, but owing to the high resistivity of the surface layers in pumice country, such work requires either a high applied voltage or very sensitive meters; the equipment available was found unsuitable for this purpose. Moreover, in attempting deeper penetration, the shielding effect of the good conductor provided by the shallow hot water is a serious handicap.

It has been argued that the results of this survey could have been predicted without prospecting, because the ground-water pressure gradient always has a component directed toward the nearest stream or river, so that hot and saline water will be diverted from Onepu toward the Tarawera River, and coming from higher country to the west, some of it will inevitably pass beneath the river and approach it from the low-lying plain to the east. However, the fact that steam is now obtained from 2,000 ft drillholes to the east of the river indicates that the movement of the hot water is here predominantly vertical, and that the distribution of shallow hot water may be taken as a pointer to its deeper distribution.

In contrast to the success of this survey, similar work at Wairakei has been less helpful. There are several reasons for this. In the first place neither the depth of the water table nor the surface geology is uniform. In many parts there is a less abrupt transition from hot to cold country than at Kawerau and there is a large area in which the hot waters are not saline. Moreover, at Wairakei the shallow hot water is more widely distributed than the deep, especially towards the Waikato River. Nevertheless, it may be possible to overcome many of these drawbacks with better instrumentation and modified techniques.

SEISMIC SURVEY

Twelve miles of refraction seismic survey, shot over the Kawerau plain, showed in most places a strongly refracting horizon at depths varying from 200 to 500 ft. This correlates with the top of more than 1,000 ft of rhyolite and rhyolite breccia later penetrated by drillholes. The longitudinal seismic velocity of this refractor was about 10,000 ft per sec., being higher or lower where silicification or hydrothermal leaching has occurred. The overburden velocity was very varied, ranging from 5,800 ft to about 7,200 ft per sec.; the high values mark silicified areas and possibly also remnants of pumice breccia within the alluvium.

As is usual in this type of work, the seismic noise level near the hydrothermally active areas was found to be very high, probably owing to agitation at the water table by steam and gas bubbles. Also of interest is the failure to record energy arrivals at geophones situated in an active area, although arrivals were satisfactorily recorded at points on the opposite side of the active area from the shot. It is suspected that this phenomenon is due to the damping or dispersive effect of steam and gas bubbles at the water table, and that this damping or dispersion only occurs where the energy paths cross the water table in an area sufficiently hot or sufficiently gassy for numerous bubbles to be present.

Exploitation

Three of the shallow temperature holes drilled by D.S.I.R. spontaneously discharged steam and water mixtures, while a fourth gave a voluminous flow of hot water. The output of one hole was measured by calorimeter; although only 205 ft deep and lined with 3-inch casing to 130 ft, the discharge amounted to 37,000 lb per hour, with an enthalpy of 300 BThU/lb. This was sufficient indication of the possibilities of the field to warrant deeper tests of the high-pressure resources.

Three deeper holes were drilled by Ministry of Works crews under the project engineer, Wairakei; No. 1 reached 1,476 ft on the east bank of the Tarawera River, No. 4 reached 1,690 ft in the active area to the west, and No. 5 was abandoned at 1,409 ft close to the site of the papermill (Fig. 7). The last hole confirmed that steam was not obtainable at the mill itself, as predicted from prospecting results. Temperatures above 100° C were recorded between 500 and 600 ft from the surface, but below this the rock alteration was more consistent with ancient atmospheric weathering than with hydrothermal activity (Mr A.

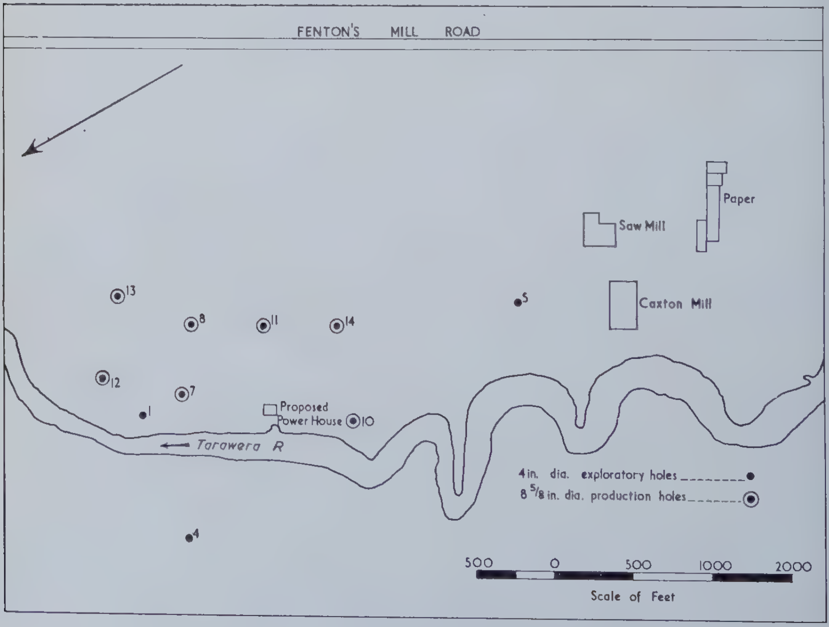

Fig. 7.—The location of Kawerau drillholes.

Steiner, pers. comm.). Holes 1 and 4, on the other hand, gave high enthalpy discharges. Seven 2,000 ft production holes were therefore drilled by Messrs Fletcher-Bechtel-Raymond and Brown Drilling Company under contract to the Tasman Pulp and Paper Company Limited, to supply steam for process and power purposes in the mill.

Drillhole Data

Kawerau differs from Wairakei and Waiotapu hydrothermal fields in the presence of rhyolite flows, in place of ignimbrite, in the drilled rock sequence, and in this respect it resembles Rotorua and the south extension of Wairakei. However, the two formations appear to be similar in their influence on the hydrology. Like ignimbrite, the rhyolite is intrinsically relatively impermeable, and it is probably true that movements of water are confined to joints and fault planes to a much greater extent than in the sediments above and below. During drilling at Kawerau, mud circulation was frequently lost in the upper rhyolites, but the lower flows were much tighter. Drillhole temperature curves tend to be rather linear through the lower rhyolites, confirming the lower permeability and increased importance of conductive heat flow at these levels.

In other respects temperatures are similar to those at Wairakei, crossing the boiling-point curve occasionally in the less permeable layers (compare Studt, 1957). The maximum recorded temperature was 253° C. at 1,626 ft in hole 4, and some of the production holes, although logged before regaining equilibrium after drilling, show temperature peaks at 1,600 to 1,800 ft, suggesting influx of hot water through a permeable stratum at this depth. With tight rhyolite above as a confining bed, this stratum no doubt constitutes an aquifer in which the hot water is stored.

Productivity

The output from holes 1 and 4 was found to be quite comparable with that of the 4-inch diameter holes at Wairakei, the steam fraction from 1 being the best yet obtained, owing to the abnormally high enthalpy; in other respects the characteristics of these holes were such as could be expected in geothermal projects. At Wairakei, a high enthalpy is found only in holes on the margin of the hot area or holes which tap the country immediately below an impermeable formation.

The seven $8\frac{5}{8}$-inch diameter production holes are all drilled to about 2,000 ft, producing through perforated casing, with only a short length of open hole. Four of these are good producers; two are average and only one has a low output, which might be due to inadequate perforation. The mass output from the most productive holes is rather low, but high enthalpy again makes the steam fractions comparable with the best at Wairakei. The fact that these holes, producing from several hundred feet deeper than No. 1, also have high enthalpy indicates that this feature is due to the situation of the holes on the boundary of the hot area rather than to the influence of any impermeable beds. Unlike hole 1, the deeper production holes are without exception abnormal, in that the enthalpy of the discharge rises with rise in wellhead pressure. This phenomenon is very rare at Wairakei, having been recorded only at hole 40. Hole 40 is again on the boundary of the hot area, and it earlier showed normal characteristics, i.e., nearly constant enthalpy. It is thought that the change was brought about by the approach of cold water from the surrounding country, induced by the high rate of exploitation, but just how cold water causes this change is not known.

Despite these indications that they are situated on the margins of the area, the combined heat flow of all the production holes has been estimated at 68,000 k.cal./sec. at a wellhead pressure of 100 lb per sq. in., which is 2·7 times the estimated natural heat flow. The present draw-off from Wairakei exceeds the natural heat flow by a similar amount, but in both fields the output probably comes largely from heat stored in the aquifer.

GRAVITY SURVEY

It has been stated that Kawerau lies on a northern extension of the Rotorua-Taupo depression, but it is desirable to examine the regional structure in greater detail for possible clues to the origin of the hot springs. An unpublished gravity survey of the Whakatane area has shown that the depression is associated with a gravity deficiency amounting to 45 milligals (Bouguer) at Thornton on the coast, and declining toward the Mesozoic outcrops at Whakatane and Pukehina. West of Matata, however, the anomaly is much reduced, and greywacke gravels at this point suggest that basement is at no great depth. Inland, the anomaly extends in a south-south-westerly direction with gradually reduced amplitude. The Kawerau survey extended the coverage southward from Te Teko, where the main anomaly is confined to the Tarawera and Rangitaiki valleys.

This survey was made with a North American gravity meter, and the results are shown in the form of Bouguer anomaly contours in Fig. 8. In computing these results, the following corrections have been applied:

(1) Latitude, corrected according to the 1930 International Formula.

(2) Terrain, corrected to a radius of 560 ft, density 2·0.

(3) Elevation, sea-level datum, density 2·0.
In the low altitude and low relief of the Kawerau country, departures from this density are insignificant, except on owharoite outcrops in the south-east corner of the map. Even here the error is small and is neglected. Both baro-

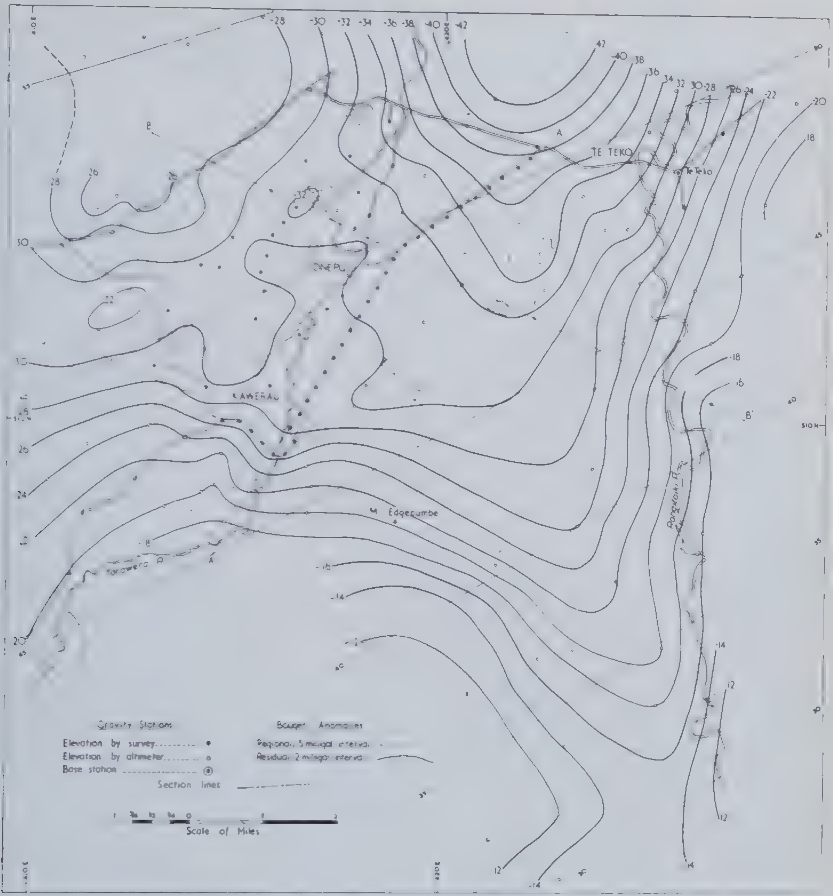

FIG. 8.—Kawerau gravity survey, regional and residual anomalies.

metric and surveyed heights were used (see Fig. 8), giving accuracies of 1 milligal and $1/10$ milligal respectively.

(4) Regional Anomaly, computed by Dr E. I. Robertson on the basis of a large number of stations located on the Mesozoic rocks of the North Island; regional anomaly contours are shown on Fig. 8.

This last correction purports to remove all variations of gravity having their origin in or below the Mesozoic basement, leaving only variations originating within the covering strata or in the topography of the contact between basement and cover. Since the values of regional anomaly are extrapolated from a sedimentary into a volcanic province, it is not certain that all deep-seated variations are removed by this correction, but from the point of view of the Kawerau survey this is unimportant.

The densities of the more important rock formations are set out in Table 2; except in the limited areas in which andesite occurs, there is a density contrast of at least 0·4 g per cc between the Mesozoic greywacke and the younger rocks. Nothing is known of the density in the area covered by this survey, of the lower covering strata, but if it be assumed that the overall contrast is 0·5 g per cc, it is possible, by using a standard two-dimensional graticule, to build up a profile of the basement topography that will satisfy the field observations along a given traverse.

TABLE 2.—Some Physical Properties of Major Rock Types at Kawerau.

Rock type	Age	Saturated density g/cc	Magnetic susceptibility c.g.s. × 10—6	"Q"* factor
Greywacke	Mesozoic	2·59	30	—
Andesite, Manawahe	Pliocene	2·41	950	3
Andesite, Edgecumbe	Recent	2·53	1900	—
Owharoite	Pleistocene	2·18	770	4-10
Rhyolite		2·18	550	0-40
Pumice Breccia		1·66	380	—
Pumice Sandstone		1·51	0	—

*The "Q" factor is the ratio of the remanent to the induced magnetic polarization in the present earth's field.

This has been done for line AA (Fig. 8) and the resulting profile, together with a comparison of the computed and observed gravity values, appears in Fig. 9a. According to this interpretation, the basement rises from over 7,000 ft depth in the north to between 5,000 and 6,000 ft beneath Kawerau. Close to Mt Edgecumbe there is evidence for a fault at which basement is upthrown about 3,500 ft to the south.

Along line BB it is found impossible to match the observed values with any computed basement profile. This is because the small area of high gravity values immediately west of the Tarawera River is too localized to be interpreted in terms of basement at a depth consistent with profile AA. Nettleton (1940) gives some simple formulae relating the width of an anomaly to the depth of the body giving rise to it. If, for instance, this body has the form of a horizontal cylinder, the depth to its axis would be equal to the distance in which the gravity anomaly falls from its maximum to half its maximum value; that is in the present instance about 2,000 ft. But if the cylinder were continuous with the main mass of greywacke at 5,000 ft, with its axis at 2,000 ft, then its upper surface would crop out. The axis may be brought closer to surface by distorting the body into more sheet-like form, but dis-

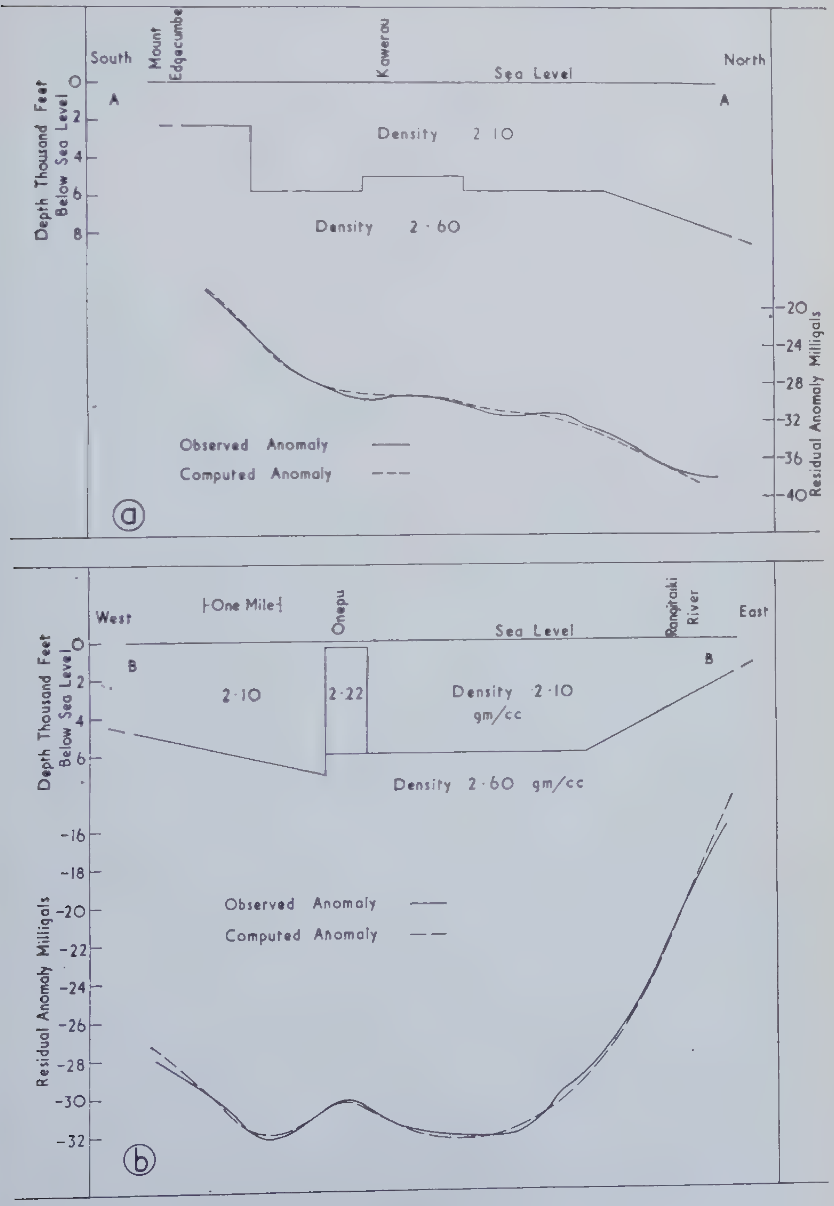

FIG. 9.—Cross-sections computed from gravity anomalies.

tortion into dyke-like form will not lower it greatly; moreover, the latter form is not typical of the basement rocks. It must be concluded, therefore, that the local anomaly has its origin within the cover.

It is possible that the anomalous body is an isolated remnant of dense Tertiary sediments, but a comparison of Figs 3 and 8 shows that the local anomaly corresponds so well with the location of the hydrothermal area as to suggest that the two are genetically related. There may, for instance, be a dense rhyolitic intrusion, or less dense rocks may be made dense through silicification by the hot water. In Fig. 9b, therefore, the local anomaly is attributed to a limited volume of covering strata with intermediate density, which enables a basement profile to be drawn which is consistent with all the data.

The depths to basement shown in these two profiles must be regarded as minima, owing to the uncertaintly as to the density of the lower covering strata, for the overall density contrast may be smaller than has been assumed here.

Although there is geological evidence for faulting along the Rangitaiki River, profile BB shows a slope of less than 30° here. This interpretation fits the data better than the single fault, but a reconnaissance survey such as this is not capable of very precise interpretation, especially since observations are lacking east of the river. Step faults would simulate a slope from the gravity point of view, or it is possible that this particular fault antedated its burial long enough for erosion to mature its scarp. At the opposite end of line BB the basement is over 4,000 ft deep, although Grange and Macpherson regarded the Manawahe volcanics as the western margin of the graben. It is probably better to regard the depression in the Kawerau area, not as a graben, but as merging south-westwards into the very extensive depression occupying the central portion of the North Island.

The fault at the south end of line AA is worthy of note, for it is likely that Edgecumbe volcano owed its origin to this feature, which in turn is probably associated with powerful east-west faulting along Lakes Rotoma, Rotoehu, Rotoiti, and Rotorua, to the west of Kawerau. The Edgecumbe fault marks the north end of a third greywacke block, similar to those of Whakatane and Awakeri; although greywacke does not crop out here, there are isolated exposures in the forested country to the south.

MAGNETIC SURVEYS

A total force aeromagnetic survey at 5,000 ft above sea-level has covered most of the Quaternary volcanic belt of the North Island (Gerard and Lawrie, 1955). The map shows a drop of about 250 gamma from the Manawahe volcanics to Mount Edgecumbe, but apart from this it is remarkably featureless in the Kawerau neighbourhood. Neither Edgecumbe itself nor the edge of the owharoite sheet shows any marked influence on the contours, from which it can be concluded that neither extends far below the surface.

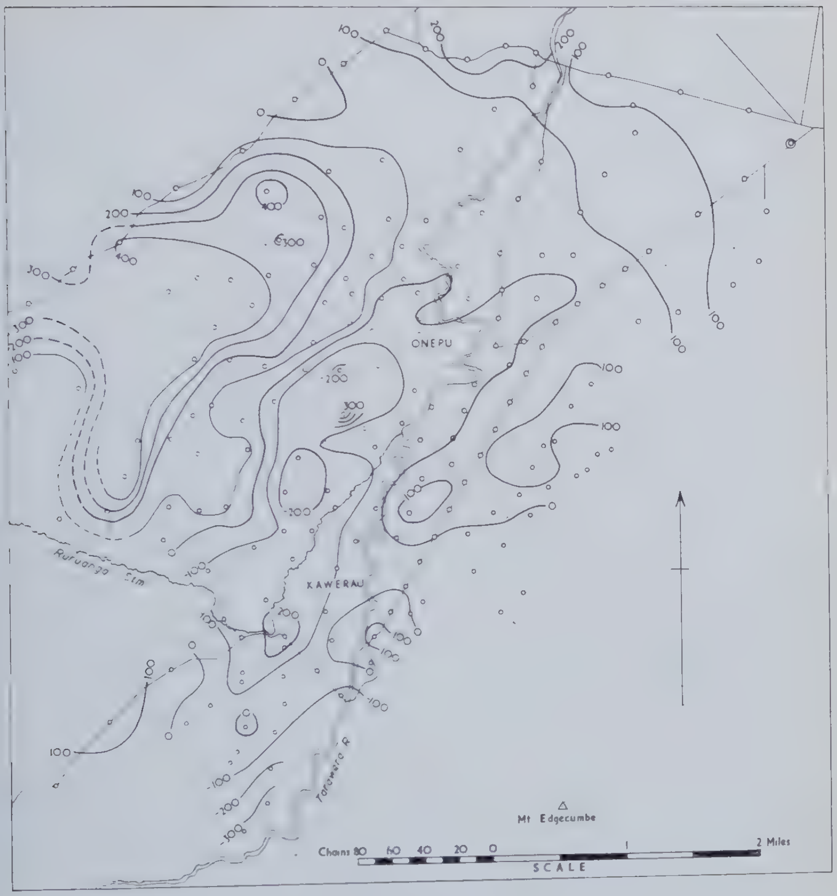

FIG. 10.—Surface magnetic survey of the Kawerau neighbourhood.

In order to supply additional detail in the neighbourhood of Onepu, a vertical force ground survey was made with Watts balances. This work is shown in Fig. 10; iso-anomaly contours are drawn at 100 gamma intervals relative to an arbitrary base, latitude and diurnal corrections having been applied. Topographical effects are insignificant, except around Mt Edgecumbe. Here again, the gradient from Manawahe is prominent, the lowest intensities being recorded in the hydrothermal area. Some magnetic relief in the north-west may be due to rhyolite flows; elsewhere there is little relief, although rhyolite is known to underlie much of the surveyed area. This implies either that the rhyolite is present in an unbroken sheet, and cannot be detected by such a survey, or that the rhyolite is no more than weakly magnetic.

Magnetic susceptibilities for the major rock types are included in Table 2, also in certain cases the range in the ratio of remanent to induced polarization. The only rocks capable of giving much magnetic relief are the andesite, owharoite, and rhyolite, and the major anomalies in this part of the country are associated with rhyolites. But the range of field intensities over the rhyolite rocks is not capable of explanation in terms of size and depth of body and magnetic susceptibility, being largely due to the wide range in remanent polarization.

In much of the early magnetic mapping it was assumed that decreased field intensities over rhyolite adjacent to hydrothermal areas implied hydrothermal alteration of the rocks. But in many cases no such alteration can be seen and the susceptibility is normal, but the remanence is low. Whether this is truly indigenous, or whether it is a symptom of reheating or undetected alteration is not known, and the finely disseminated state of the iron ores in these rhyolites discourages investigation. Hatherton's work (1954) on the New Zealand ignimbrites has indicated the dependence of remanent polarization on rate of cooling and subsequent reheating, but it is possible that there is also dependence on the precise composition of the iron ores, on the mineral phases separating out during cooling, and on the particular intergrowth of domains resulting from this process, as has been shown by Japanese workers in this field.

However this may be, it must be accepted that the absence of high magnetic intensities at Kawerau does not preclude the presence of isolated buried rhyolite masses, for the ratio of remanent to induced polarization in some of the samples from this locality is low.

ORIGIN OF THE HOT SPRINGS

Macpherson (1944, p. 69) cited Onepu hot springs as evidence for the northward continuation from Tarawera of a zone of north-east faulting. Many authors have drawn attention to the obvious association of hot springs (or fumaroles) with faulting at Waihi, Waikite, Wai-Mangu, and Te Kopia; the association is present at Waiotapu and Wairakei also. But this observation is not of great value, for such faults are very common in the North Island volcanic belt, and only a fraction of them carry hot water. These faults frequently facilitate the rise of the hot water to surface, but other factors are involved in its origin at depth.

The association which has been shown to exist between the Onepu hydrothermal area and certain geophysical anomalies is not unique, for it is closely duplicated at Rotorua. Again there is a minor positive gravity anomaly, superimposed upon a major negative structure and coinciding in extent with the hot water; there are rhyolite domes close by and rhyolite flows beneath a cover of pumice sediments, and there is low magnetic intensity (Jones, 1948; Modriniak, 1949) despite the existence of this rhyolite. At Waiotapu, ignimbrite replaces rhyolite in the drilled rock sequence and a small positive magnetic anomaly accompanies the minor gravity anomaly, but other features are very similar. At Wairakei, however, the position is different, for the hot water is found over a large positive gravity anomaly, against which background a minor positive anomaly would be difficult to recognize. Both ignimbrite and rhyolite are found by drilling.

It is believed that the small geophysical anomalies at the first three locations mark intrusions, probably of rhyolitic composition, along a basement fracture, although silicification may also be a contributary factor. Hot water may come direct from the intrusion, but it is more likely to come from greater depth, travelling up the margins of the intrusion and along faults created by its emplacement. These faults generally run north-east, irrespective of the orientation of the intrusion itself, being controlled by the stress pattern in this region.

While this theory does not explain the origin of the heat or of the hot water, it does have a bearing on such modes of origin as have been considered in detail by Healy (1956). The magmatic body associated with the hot water at the three localities mentioned above is quite small, and it does have surface expression. As Healy has pointed out, it is unlikely itself to be capable of maintaining an extensive hydrothermal system for long. But as it is injected through the basement, and as it contracts on cooling, it may open up paths through which magmatic solutions can rise from much deeper sources, or through which meteoric water can descend to great depths to be heated conductively. This compares very closely with the association of the hot water and young basaltic dykes in Iceland (Einarsson, 1937).

In that these aspects of the hot spring problem are masked at Wairakei by the different setting, it is considered that the Kawerau survey has made a useful contribution to the understanding of the problem, even though the final solution may not be the same for all hydrothermal areas.

ACKNOWLEDGEMENTS

The author is indebted to the engineer-in-chief, Ministry of Works, for data relating to exploratory drillholes at Kawerau, to the Tasman Pulp and Paper Company Ltd., for data relating to the production holes, and to Mr R. L. Roud of Rotorua, for survey information.

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PLIOCENE SHELL BEDS SOUTH OF THE MANUKAU HARBOUR

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Summary

Shell beds exposed at the surface and others drilled at depths down to 200 ft below sea-level are of the same age and facies as the Otahuhu shell bed. There is no evidence for deformation of these Pliocene sediments.

Introduction

Whilst carrying out ground-water and other economic surveys within Franklin County, the writer learned from Mr G. Gilberd, well-driller, of Pukekohe, of a shell-bed horizon which he believed to be tilted to the west. From drillhole information in the nearby Mangere area (see Fig. 1), Firth and Page (1936) also considered (p. 325) "that the whole Pleistocene formation of the area, though essentially undisturbed, appears to have a slight dip to the north-west."

The position and logs of holes containing records of shell horizons in the southern Manukau area were kindly supplied by Mr Gilberd, and at a later date the writer took an opportunity to test if the area had undergone structural deformation or regional movements.

Fossil samples N47/542, 546, and 548 were collected from drilling sumps associated with holes 14, 12, and 1 respectively (Figs 1 and 2). A usual drilling practice is to dig a sump in which the cuttings collect and from which the water is re-used for drilling. From time to time the sump is emptied of cuttings except for the last few feet drilled, which, for most holes in the area under consideration, was a shell horizon (usually an excellent aquifer). Where the sump has not been concreted over, this bed can be found, but the older the hole the more difficult it is to locate.

Kaawa Formation

Marwick (1948) named the marine beds containing the Otahuhu faunule, the Otahuhu Formation. Although the faunules described below are the same facies, and distinct from the facies faunule at Kaawa, they could be of the same age (for further details, see section on correlation and environment). The beds of the Otahuhu section appear to be more muddy than those of the section at Kaawa (Gilbert, 1921; Henderson and Grange, 1926; Kear, 1957), but outcrops and drillholes of the southern Manukau area show that the Otahuhu faunas are found predominantly in sandstone. Hence these marine beds of Pliocene age are considered as the Kaawa Formation rather than the Otahuhu Formation. The term Otahuhu is best retained for one of the distinct facies faunules found in the Kaawa Formation.

Distribution

The position and logs of drillholes and outcrops disclosing shell horizons are shown in Figs 1 and 2. Other details are given in Table 1.

TABLE 1.—Data of Drillholes.

No.	Owner	Grid ref. N47	Height* (ft)	Remarks
1	Waiuku Council	265114	130	Sample N47/548.
2	B. J. Hosking	264196	125	Log unattainable. 496 ft deep. Shell bed from 436 ft onwards.
3	K. J. Hosking	277234	5	
4	McMikan	292245	80	Probable terrace.
5	McInnes	291308	?15	Terrace.
6	Hogwood	310255	40	Red shingle with shells. Good water, 130 ft casing.
7	N. Litchfield	317240	75	
8	N. Litchfield	316235	120	Probable dissected 120–130 ft terrace.
9	Lands and Survey	319219	60	
10	Lands and Survey	324224	120	Dissected 120–130 ft terrace.
11	Pearson Bros.	329212	c120	Exact position not located.
12	L. Clarke	353208	210	On 200–230 ft terrace (N47/f542).
13	Taylor	337248	200	On 200–230 ft terrace.
14	Watt	343274	65	N47/f546
15	Marshall	343275	70	
16	Pukekohe Golf Club	403262	120	Dissected terrace.

*Heights by altimeter above sea-level—accurate to within 10 ft.

Lithology

In the southern Manukau region, the Kaawa Formation consists mainly of a moderately compacted, coarse to medium, uncalcareous sandstone interbedded with shell beds. Small rounded fragments of jasperlite, obsidian, banded rhyolite, rare basalt, argillite, and Waitemata Sandstone are associated with some of the shell horizons.

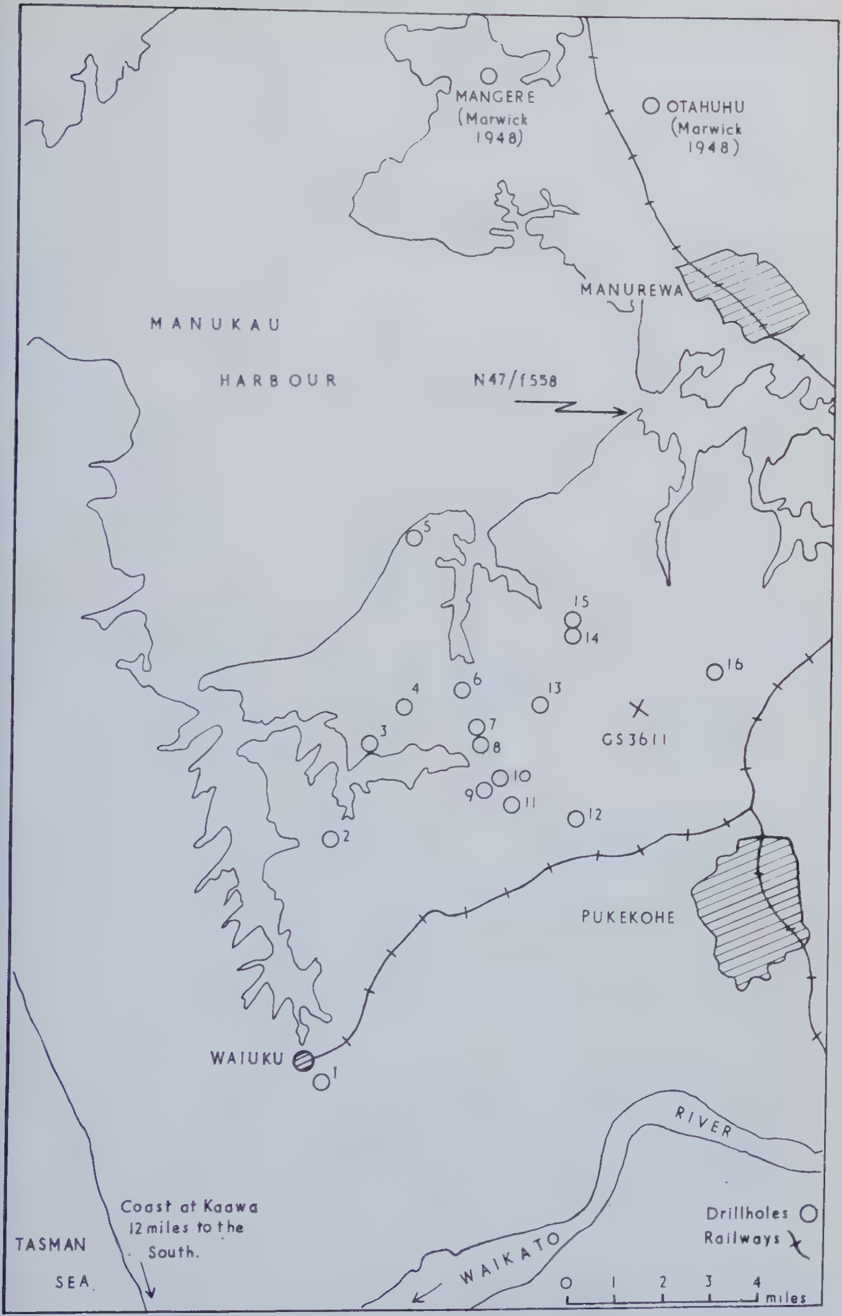

Fig. 1.—Distribution of drillholes and surface outcrops that contain the Otahuhu faunule.

Paleontology

The following lists of macro-fossils have been identified by Dr C. A. Fleming, although only fragments of shells were present in the drillhole samples.

Sample GS 532, N47/535: Park (1885) collected GS 532 from brown sand and gravel on the south side of the Manukau Harbour near Whangamaire Creek. Dr Fleming lists the following species in Park's existing collection as:

Modiolaria impactus Hermann (abundant)
Maoritellina sp.
Macomona liliana Iredale or *williamsi* Laws
Leptomya retiaria or *breviformis* (ext. cast)
Zenatia cf. *flemingi* Marwick
Dosinia ? powelli Marw.
Tawera sp.
Venericardia sp.
Cuspidaria trailli Hutton
Many Cerithiidae (difficult to determine because apices not usually preserved)
Zefallacia n.sp. (not *lawsi* Marw.)
Zaclys sp.
Ataxocerithium sp. (perhaps more than 1 sp.; not *kaawensis*)
Zeacumantus sp. (not *delicatus* Marw.)
Struthiolaria aff. *firthi* Marw.
Zegalerus sp.
Baryspira sp.
Leaves.

Sample GS 6701, N47/558: This sample was collected from the south Manukau Harbour coast, half-way between Karaka Point and the end of Urquhart's Road. Here the Kaawa Formation is horizontal and consists of a 2 ft thick shellbed overlying 6 in. to 1 ft of fine to medium, carbonaceous pebbly sandstone which rest unconformably on Waitemata sandstones. The unconformity coincides with the present-day wave-cut platform. The following species were determined from casts:

Ostrea sp.
Dilora lorea Marw.
Dosinia (*Raina*) *powelli* Marw.
Chione stutchburyi or *tamakiensis* Marw.
Tawera subsulcata or *duobrunnea* Marw.
Eumarcia (*Opimarcia*) *healyi* Marw.
E. ?kaawensis Marw.
Spisula (*Spisulona*) *couttsi* Marw.
Zegalerus tumens Finlay
Cerithiidae (abundant but difficult to determine because apices not usually preserved).
Zefallacia lawsii Marw.

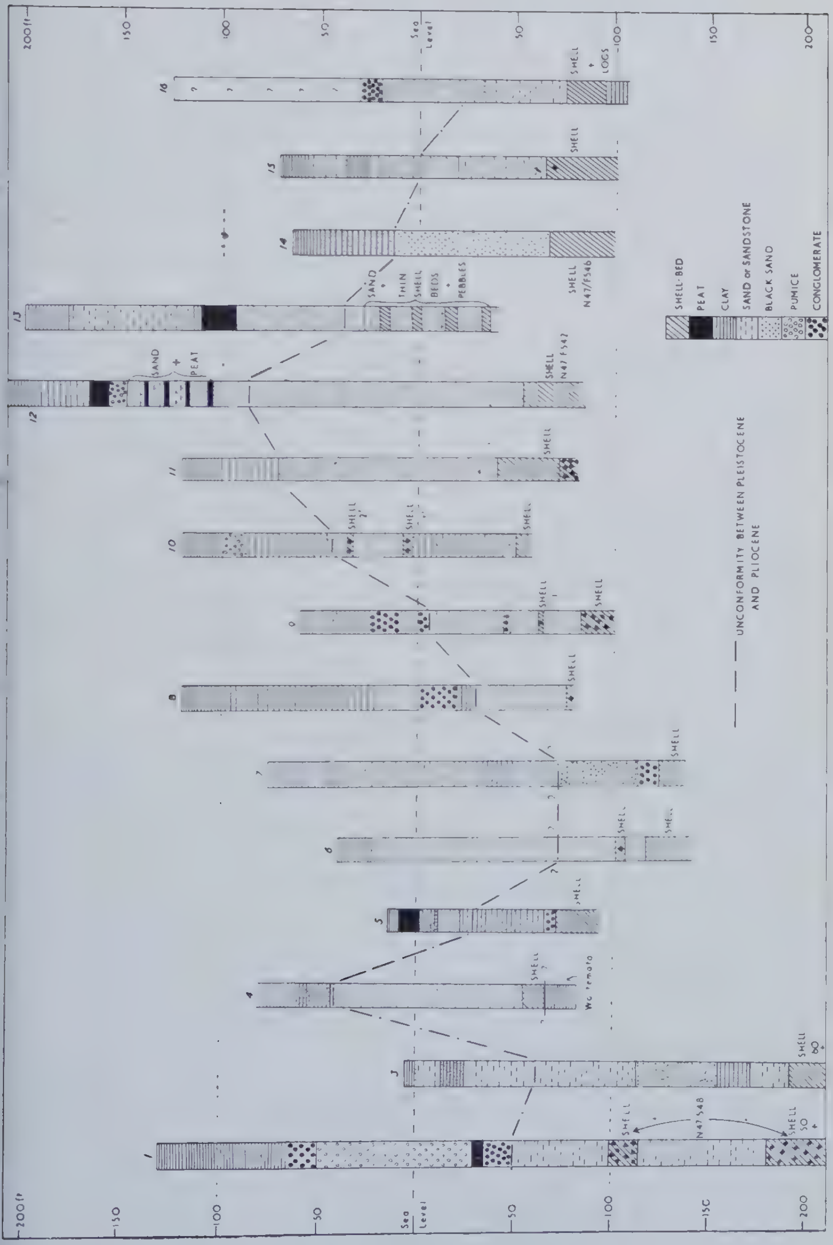

FIG. 2.—Sections of drillholes showing the horizons in which shell beds containing the Otahuhu faunule are known to occur. Scale on margin shows position (in feet) above and below sea-level.

Zaclys sp.
Zebittium or *Lyroseila* sp.
Zeacumantus sp. (not *delicatus* Marw.)

Sample GS 3611, N47/541: N47/541 was collected from a bank between Glassons Creek and a cowshed, a few chains north of the Waiuku-Runciman main highway, and is a re-collection of GS 3611, which has been described by Marwick (1948). Both collections were made by Mr A. C. Bettany, Franklin County Engineer. This outcrop has since been partially destroyed. The species marked with an asterisk in the following list are additional to the fauna described by Marwick.

Glycymeris (Manaia) sp.
*_Zenatia_ sp.
*_Mactra_ sp.
*_Angulus gaimardi_ Iredale
*_Dosinia_ (?_Phacosoma_) sp.
*_Dosinia lambata_ (Gould)
Tawera sp.
*_Bassina_ sp.
*_Chione_ sp.
Zethalia coronata Marw.
Polinices sp. cf. *dingleyi* Marw.
*_Hartungia postulata_ Bart.
*_Baryspira_ cf. _pacroa_ Fleming

Sample GS 6328 N47/546 (Drillhole 14; top of shell bed approximately —65 ft:

Nucula hartvigiana Pfeiffer
Glycymeris (*Manaia*) sp.
?*Glycymeris* (*Glycymerita*) sp.
?*Phialopecten triphooki* (Zitt.)
Amphidesma (*Paphies*) cf. *australe* (Gmelin)
?*Maorimactra* sp.
Tawera duobrunnea Marw.
Bassina cf. *katherinae* Marw.
Eumarcia sp.
Taxonia tesserata Marw.
?*Stiracolpus* sp.
Sigapatella sp.
?*Polinices* sp.
Zethalia coronata Marw.
Coelotrochus n.sp. aff. *tiaratus* (Q. & G.)
Paxula sp.
Xymene sp.
Baryspira sp.
Marginella sp.
Pervicacia aff. *tristis* (Desh.)
Other gastropod fragments not determined.
Balanus plates.

N47/542, F9621 (Drillhole 12; top of shell bed, approximately — 60 ft): The following Foraminifera were identified by Mr N. de B. Hornibrook: *Streblus aoteanus* Fin., which is known from the Kapitean and younger beds, and *Elphidiononion* aff. *simplex* (Cush.), which occurs in the Kaawa beds and is thought to be no younger than Opoitian.

Sample (GS 6322, N47/548 (Drillhole 1; two shell beds, tops at — 100 and — 180 ft):

Glycymeris sp.
?*Taras* (*Zemysia*) sp.
Mactra (*Cyclomactra*) *williamsi* Marw.
Amphidesma (*Paphies*) cf. *australe* (Gmelin)
Tawera duobrunnea Marw.
?*Eumarcia* sp.
Anchomasa cf. *similis* (Gray)
Zegalerus sp.
Zethalia sp.
Coelotrochus aff. *brownei* Flem.
Venustas cf. *hawera* Oliver
Zymene cf. *coctor* Marw.
Cominella (*Cominista*) cf. *altispira* Marw.
Baryspira (*Pinguispira*) sp.
?*Pervicacia* sp.
Balanus sp.

Age, Correlation, and Environment

Dr C. A. Fleming correlates the above faunas with the Otahuhu and Mangere faunas described by Marwick (1948). The tops of these shell-beds are — 45 ft and — 95 ft respectively (Fig. 1). The only other collection of about the same age and in a nearby area, is that from Kaawa, which is a few feet above sea-level. Although "direct age comparison of the Otahuhu faunule with that of Kaawa is limited by the marked dissimilarity in their constitutional make-up," Marwick (1948) cites evidence for believing that the Kaawa faunule is Opoitian and the Otahuhu is Waitotaran in age. Concerning the latter, however, he stated that "it must be acknowledged that evidence for an Opoitian age is almost as strong." Laws (1950), on the basis of the micro-mollusca, concluded that the "Otahuhu beds are very close in age to those at Kaawa Creek, probably slightly younger, though not yet as high as the basal Waitotaran." Slight foraminiferal evidence (see N47/f542 above) also suggests that the Otahuhu faunule may be Opoitian in age.

Both Laws (1936, 1950) and Marwick (1948) agreed that the Kaawa (10 to 15 fathoms) and Otahuhu (5 to 10 fathoms) faunules accumulated in shallow water, but that they are of very different environments. These environments are likened by Marwick to "conditions not unlike those now prevailing in the sea not far from the respective localities."

PLEISTOCENE TO RECENT SEDIMENTS

The Pleistocene to Recent sediments have not been studied in detail, but all known outcrops are mainly pumice with interbedded peats. Correlation of drillers' logs is uncertain under the best of conditions. For example, some of the reported gravels could be scoriaceous basalt; the failure to record pumice does not necessarily mean its absence; and the black sand could be tuffaceous horizons. Nevertheless, unless there has been structural deformation, the drillholes show an unconformable relationship of the Pleistocene with the Pliocene. The suggested contact (Fig. 2) is based mainly on hardness reported—the upper beds are reported as soft sands, whereas the lower beds are often reported as sandstones.

Terrace levels, cut or built during the Pleistocene, occur at 210 to 230 ft, 100 to 125 ft, 70 to 80 ft, 40 to 50 ft, 15 ft, and 7 to 10 ft above present sea-level. All of these have been recognized by Brothers (1954) in the South Kaipara region, 30 miles to the north. These are correlated with the world-wide Milazzian to Flandrian sea-levels of early Pleistocene to Recent age.

CRUSTAL STABILITY

Marwick (1948) summarized evidence in favour of, and suggested tentatively that there has been, tectonic quiescence since the Miocene in the Auckland area. Although minor faulting, associated with Pleistocene volcanism, has been described by Schofield (in press), the widespread occurrence of early Pleistocene terrace heights, which may be correlated with those of Europe (Brothers, 1954), show that major tectonic movements have been absent for this period of time. One way of testing whether or not this period of relative inactivity extends further back in time lies in the correlation of the above-described Pliocene shellbed horizons. However, they all appear to be of the same age, and their vertical and horizontal distribution (Fig. 2) can be explained by the shallow water conditions in which they were deposited, for this must lead to a diversity of lithological sections and a lensoid distribution of shell beds.

Correlation farther afield shows that, although both Marwick (1948) and Laws (1950) agree that the Kaawa beds could be slightly older than the Otahuhu beds, the differences of environment make time correlation uncertain.

It is concluded (1) that there is no conclusive evidence of any major structural deformation since the Miocene, and (2), assuming tectonic stability, there has been regional subsidence (or a eustatic rise) of at least 250 ft during the Pliocene, for all shell beds were deposited in a similar environment of 5 to 10 fathoms. If the unsampled shell bed of hole 2 (base below — 375 ft); see Table 1) also contains an Otahuhu faunule, then regional subsidence during the Pliocene would have been greater than 425 ft.

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THE LOWER ORDOVICIAN OF CAPE PROVIDENCE: A NEW GRAPTOLITE ZONE AND A NEW SPECIES OF *SCHIZOGRAPTUS*

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(Received for publication, 23 January 1958)

Summary

New graptolite collections from Cape Providence, north of the section described by Benson and Keble in 1935, show a repetition, in reverse order, of the beds known to the south, on the gently-dipping northern limb of an assymmetrical east-west-trending anticline. Zones La 2β, La 3, Be 1, and Ch 2 were recognised. The Upper Lancefieldian Zone (La 3), not previously recognised, in New Zealand, in represented by poorly preserved graptolites, including *Tetragraptus approximatus, T. acclinans, T. decipiens,* and *Schizograptus waddickorum* n.sp. (related to the Lower Bendigonian *S. spectabilis* of Victoria); no specimens of *T. fruticosus* were identified.

INTRODUCTION

In March 1957, Mr B. L. Wood and Dr H. J. Harrington of the New Zealand Geological Survey, in the course of Four-Mile geological mapping, spent a short time examining the fossiliferous Ordovician rocks of Fiordland. Most of their stay was occupied with re-collecting faunas at known graptolite localities at Cape Providence and Kisbee Beach (Benson and Keble, 1935); but, with the hope of extending knowledge of the New Zealand Ordovician column, some time was spent investigating strata north of the lowest known fossiliferous horizon in the Cape Providence section.

Material obtained from previously known localities brought to light some minor additions to the New Zealand graptolite fauna, but this paper is concerned mainly with the northerly, newly established, localities and the implications of structure they carry. So far nothing concerning them has been recorded in paleontological literature.

Six Geological Survey fossil localities were established at and north of The Arch Stack (Benson and Keble, 1935, fig. 1, p. 247). These are, from south to north, GS 7016, 7017, 7014, 7021, 7020, and 7015. As far as the field conditions allowed, collections were made in a section across the strike so as to extend Benson's original section to the north.

The mode of preservation and quality of graptolites obtained differ from one locality to another, some being exceedingly poor. Fortunately,

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however, in most cases enough material was identified to enable fairly precise zonal determination. (For zones and symbols see Benson, 1938.)

LOCALITIES

GS 7016 and GS 7017 are from beach boulders at The Arch Stack, and both contain small numbers of poorly preserved graptolites. Both are characterized by Anisograptids (forms previously referred to genus *Bryograptus*, see Bulman, 1941) and Clonograptids. The few forms that could be given specific names indicate Middle Lancefieldian age. As no Dictyonemata have been found, the assemblage probably belongs to the higher subzone of the Middle Lancefieldian (La 2β).

GS 7014. $\frac{1}{2}$ m. north of The Arch Stack. Preservation of graptolites is very poor. Among the Anisograptids, at least three specimens of *Adelograptus hunnebergensis* (Moberg) were distinguished; one of the other forms examined has marked resemblance to *A. antiquus* (T. S. Hall). Both these forms are confined to Middle Lancefieldian strata in Victoria. As in GS 7016 and GS 7017 no Dictyonemata have been found.

GS 7021. 1 mile north of The Arch Stack, tip of subdued headland in middle of bay. This collection represents a new zone in the New Zealand Ordovician sequence and is treated in greater detail below.

GS 7020. $1\frac{1}{2}$ miles north of The Arch Stack. Only two genera are represented here; one by specifically indeterminable juvenile Anisograptid forms, the other by abundant *Tetragraptus quadribrachiatus* (J. Hall). The range of *T. quadribrachiatus* is fairly extensive in the Lower Ordovician of both Victoria and New Zealand, but the species has a strongly marked maximum in the Lower Bendigonian (Be 1). Strata represented by this collection are referred, with some hestitation, to this zone.

GS 7015. At the "Northern Arch Stack" (approximately 2 miles north of The Arch Stack). A rich and well-preserved graptolite assemblage, characterized by the presence of early varieties of *Isograptus caduceus*, i.e., *I. caduceus* var. *primula* Harris, and *I. caduceus* var. *lunata* Harris. The latter ranges from Middle Chewtonian to Lower Castlemainian in the Victorian sequence, while the former is confined to Ch 2 (Harris, 1933). The above assemblage is therefore regarded as of Mid-Chewtonian age.

STRUCTURE AND ZONAL SUCCESSION

It was hoped that collections north of The Arch Stack would prove a downward extension of the Ordovician column. The zonal determinations of collections made north of The Arch Stack show, however, that the beds repeat in reverse order the section known farther south. The beds beyond The Arch Stack form the gently dipping northern limb of an east-west trending, strongly assymmetrical anticline, the southern limb of which dips very strongly into a tight syncline already described by Benson.

Previous work has shown that the zones represented in the southern limb are La 2α, La 2β, Be 1, Be 4, Ch 1, Ch 2, and Ch 3.

One of the zones missing, La 3, in Victoria consists of strata lying between the first appearance of *T. approximatus* and that of *T. fruticosus* (J. Hall). This zone has not previously been identified in New Zealand. Benson and Keble (1935, p. 259) comment: "It appears . . . that the L1 [La 3] zone is either very thin, or unrepresented in the New Zealand succession." Be 2, the zone of 4-branched *T. fruticosus* with complete absence of 3-branched *T. fruticosus* and *T. approximatus*, is represented only by a pebble, while Be 3 (entry of 3-branched and survival of 4-branched *T. fruticosus*) is not known in New Zealand.

Collections from the northern limb were examined with a hope of bridging some of the gaps in the known sequence in the southern limb. A single collection, GS 7021, appears to represent part of the missing zone (La 3) and will be discussed in detail.

UPPER LANCEFIELDIAN ZONE LA 3

The collection from GS 7021, about 1 mile north of The Arch Stack, is small, but contains an assemblage of imperfectly preserved graptolites that is entirely different from any so far examined. In the following list, the figures in parentheses show the number of specimens identified:

	Stratigraphical Range
Tetragraptus approximatus Nicholson (1 small)	La 3–Be 1
T. aff. *approximatus* Nicholson (1 small)	
T. quadribrachiatus (J. Hall) (3 +)	La 2β–Ch 2
T. decipiens T. S. Hall (2)	La 1–Be 1
T. acclinans Keble (4)	La 3–Be 1
Schizograptus waddickorum n.sp. (2 + fragments)	
Clonograptus sp. (fragments)	

T. approximatus occurs in both the Upper Lancefieldian and the Lower Bendigonian of Victoria (Harris and Thomas, 1938). In La 3, where it is first observed, it appears in large numbers and is accompanied by variants intermediate between it and *T. acclinans* Keble, together with some Anisograptids which, however, are not as abundant as in the Lower and Middle Lancefieldian zones. In the lowest Bendigonian *T. approximatus* is reduced to no more than a "surviving" form, while the species of greatest importance, which by its appearance marks the beginning of Be 1, is 4-branched *T. fruticosus* accompanied by *T. pendens* and numerous extensiform Didymograptids.

Although GS 7021 certainly cannot be thought to contain a "burst" of *T. approximatus*, it is otherwise completely deficient in any of the forms characterizing the Lower Bendigonian. It has, on the other hand, four specimens of *Tetragraptus* which have been referred to *T. acclinans*, and also 2 specimens of *T. decipiens*. Not a single specimen of *T. fruticosus*, the key fossil of Bendigonian rocks, has been identified. No Anisograptids have been observed.

Perhaps the most unusual feature of the assemblage lies in the comparative abundance of the genus *Schizograptus*. This genus has not been previously recorded from New Zealand. Schizograptids, judged by the available literature, have nowhere been found in large numbers or even comparatively commonly, and are seldom accompanied by numerous associated forms. The holotype of the new species described below, a rather well-preserved and nearly complete, though slightly distorted, specimen, was accompanied by several separate, poorly preserved fragments of branches in this small collection. As stated below, it has marked affinities with *S. spectabilis* Harris and Thomas of Victoria, but has sufficient distinguishing features to warrant separation as a new species. The Victorian form was obtained from Lower Bendigonian strata at Sandon.

In the light of present evidence the assemblage characterized by *Schizograptus* may be regarded as representing the lowest layers of the *T. approximatus* zone of Victoria, i.e., the base of the highest Lancefieldian (La 3) zone.

If more detailed work does nothing to discredit the above interpretation, then the *Schizograptus* horizon may be regarded as a distinct line marking the beginning of the Upper Lancefieldian zone in New Zealand.

Unfortunately, the collection from GS 7021 is a small one and the fauna it represents is by no means well preserved. It is even more unfortunate that Cape Providence is very difficult of access. Some difficulty is envisaged in re-locating the site of this collection. More than twenty years have elapsed since Benson's party visited the area, and there is no immediate prospect of a further visit. These considerations are considered justification for publishing a paper based on rather limited evidence. This latest contribution amply confirms the suggestions of previous workers that there remains plenty of scope for accurate field work at Cape Providence. Future field work will probably show the Lower Ordovician stratigraphical column at Cape Providence is by no means as incomplete as the somewhat hurried visits so far have suggested.

Schizograptus waddickorum n.sp.

(Figs 1, 2)

DESCRIPTION. Rhabdosome rigid. First order branches from a funicle 3 mm. long, 0·4 mm. thick, from which gently curved branches of second order diverge. The latter may be over 7 cm long, and increase in thickness very gradually from 0·5 mm at the point of divergence to a maximum width of 1·7 mm.

A solitary lateral branch is given off from the convex (theciferous) margin of each stipe at a distance of 1 to 2 cm from the funicle; angle of divergence varies considerably, but has never been observed to be greater than 75° nor smaller than 25°. Unlike the second order branches the lateral stipes attain their maximum breadth of 1·7 mm within 5 mm.

Thecal measurements of the best-preserved lateral branch are as follows: 11 in 10 mm at proximal end, inclined at 40 to 45°; distally more widely spaced (9 to 10 in 10 mm), inclined at 35 to 70°, two and a half times as long as wide and overlapping for one-third of their length. Thecal margins straight or slightly concave, very steeply inclined (80 to 90°).

Thecae of the second order branches seem to correspond fairly closely to those of the lateral branches, but are difficult to study because of poor preservation.

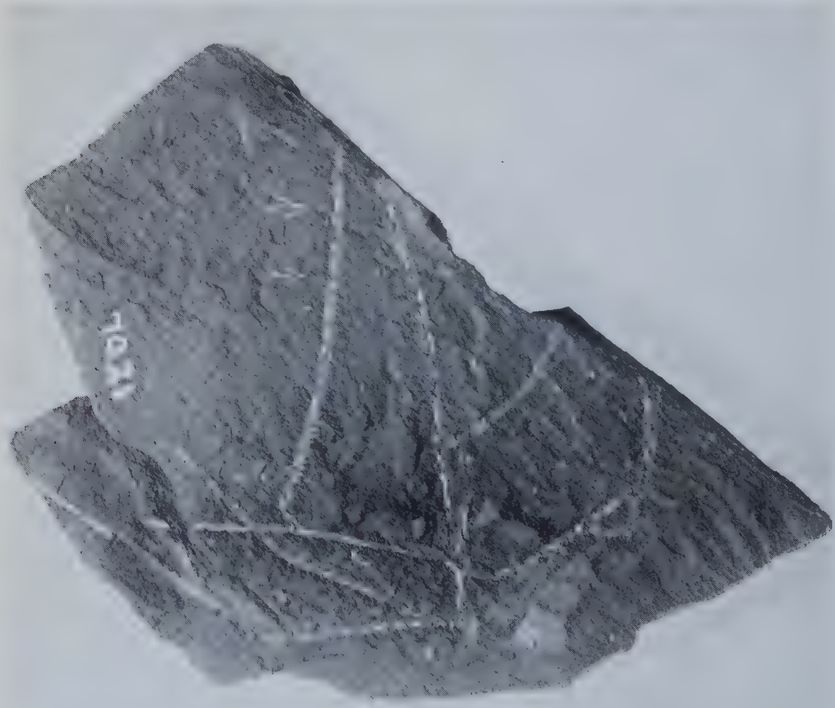

FIG. 1.—*Schizograptus waddickorum* n.sp. Holotype, × 1.
S. N. Beatus, photo.

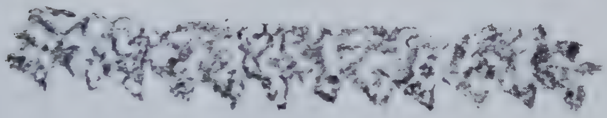

FIG. 2.—*Schizograptus waddickorum* n.sp. Holotype. Camera lucida drawing showing detail of second order branch, × 5.

HOLOTYPE AND PARATYPE. New Zealand Geological Survey.

LOCALITY. Cape Providence, Preservation Inlet (GS 7021).

AGE. Lancefieldian (La 3).

ASSOCIATED FORMS. *Tetragraptus approximatus, T. quadribrachiatus, T. decipiens, T. acclinans.*

REMARKS. *Schizograptus waddickorum* has marked affinities with *S. spectabilis* Harris and Thomas (1938), a Lower Bendigonian form from Victoria. It can, however, be readily distinguished by the shorter distance between the funicle and the points of divergence of the lateral branches, the greater length of the lateral branches and differences in thecal properties.

Schizograptus waddickorum differs from *S. quebecensis* Ruedemann (1947) and from both the allied British forms, *S. reticulatus* (Nicholson) and *S. tardifurcatus* Elles, in the absence of more than one lateral branch in each secondary stipe.

The new species is dedicated to the memory of Mr Athol J. Waddick, formerly of the New Zealand Geological Survey, Invercargill, and his brother Cyril Waddick, whose launch "Gekeita" provided transport for the Geological Survey party and for the collections described in this paper. The Waddick brothers lost their lives when the "Gekeita" was wrecked in Preservation Inlet in April 1957.

ACKNOWLEDGEMENTS

The collections were made in a limited time and under arduous field conditions by Dr H. J. Harrington and Mr B. L. Wood for the purpose of expanding the reference collections in the New Geological Survey. An opportunity is taken here to thank them both for their co-operation.

To the late Professor W. N. Benson of the University of Otago, the writer owes deep gratitude for the encouragement and help he so freely gave. Special thanks are expressed to Dr C. A. Fleming of New Zealand Geological Survey, under whose supervision the work was undertaken. Finally, to Dr D. A. Brown of the University of Otago for his many helpful and valuable suggestions the writer is deeply grateful.

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NOTE ON FAULT CORRELATIONS ACROSS COOK STRAIT

By G. J. Lensen, New Zealand Geological Survey, Department of Scientific and Industrial Research.

(Received for publication, 5 December 1957)

Summary

Two methods are suggested for linking the active transcurrent faults in the North Island and the South Island across Cook Strait. One uses the average lateral displacements along the faults, the other the location of epicentres. Both methods give the same fault pattern.

Introduction

Active transcurrent faults are major features of the tectonic setting of New Zealand.

In the South Island the Alpine Fault, whose trace may be followed for more than 300 miles (Wellman and Willett, 1942), branches north-eastwards into five major active transcurrent faults. These faults are, from south to north, the Hope-Kaikoura, Kekerengu, Clarence, Awatere, and Wairau faults (Wellman, 1953). The Wairau Fault is regarded as the major continuation of the Alpine Fault.

In the North Island similar bifurcation occurs along the West Wairarapa Fault and along the Wellington Fault, which has been traced from Cook Strait to Waikaremoana (Lensen, 1958). In both Islands bifurcation takes place in a north-easterly direction.

From detailed examination of air photographs covering areas of active faults in New Zealand, the author has repeatedly observed that, after bifurcation, lateral displacement along the continuation of the original fault decreases. For features of approximately the same age the sum of the lateral displacements along the branch faults is generally less, and never more, than the lateral displacement along the original fault. With intensive bifurcation lateral displacements along the individual branch faults become very small and the system tends to die out.

If the faults do not link across Cook Strait, this dying out should have occurred in the direction of Cook Strait, and the North Island and South Island faults should increasingly bifurcate towards Cook Strait. Although the faults in the South Island branch towards Cook Strait, the displacements along the branch faults are too great, and the number of branch faults is too small, to indicate a dying out. In the North Island, the faults, if no linkage across Cook Strait exists, should bifurcate towards the south. This is not consistent with the evidence; the bifurcation, with one exception, takes place in the opposite (north-easterly) direction.

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The active faults in both islands have in common the following characteristics:

(1) Over the same width of mobile belt the number of faults is the same in both islands;

(2) The faults strike in roughly the same direction;

(3) For all the faults the lateral displacements of features of the same age are of the same order;

(4) Displacements on all faults are in the same sense, i.e., all the north-easterly faults are clockwise transcurrent.

These four consistent characteristics, together with a common tendency to bifurcate, show that the faults are all very similar in all their properties and are part of the one fault pattern, controlled by tectonic forces affecting both islands.

The existence of links across Cook Strait is, therefore, on theoretical grounds, most probable.

PREVIOUS WORK

Lyell (1857, 1868) suggested the Wairarapa Fault and the Awatere Fault to be one fault. At that time these were the only known active faults in the area. Hector (1890) regarded the Wellington Fault as a continuation of the Great Central Fault (Clarence Fault). McKay (1892) on his map linked the following:

Awatere–Owhariu Fault, Kekerengu–Wairarapa Fault, and Clarence–Wellington Fault, but in the text he linked the Wellington Fault with the Awatere Fault. In 1902 McKay linked the Wellington Fault with the Clarence Fault.

Suess (1906), largely influenced by Lyell, linked the Awatere and the Wairarapa Faults. Cotton (1954) showed that this linkage was based on misinterpretation and suggested that the Wellington Fault is a continuation of the Awatere Fault.

Wellman (1955) linked the Awatere Fault with the Wellington Fault, and the Wairarapa Fault with the Kekerengu Fault, and in 1956 Wellman, with additional evidence provided by the author, linked the Wellington and Awatere faults and the Wairarapa and Clarence faults.

Previous attempts at linkages across Cook Strait have been suggestions based chiefly on the geographic distribution of the faults.

CORRELATION BY MAGNITUDE OF DISPLACEMENT

Lateral displacement along a transcurrent fault varies with the age of the measured feature, but the average maximum displacement along any active fault in either island, tabulated below, remains fairly constant along the entire unbifurcated length of the fault.

Topographic features that indicate the maximum displacements, are generally minor spurs or the highest (oldest) terraces attributed to the Last Glaciation and are of approximately the same age. Both in Marlborough and the Wellington District most pre-Last Glacial fault features were obliterated during the Last Glaciation and most of the present features showing maximum displacement can, therefore, be regarded to be of approximately the same age. The average maximum displacements along the known faults are listed below:

South Island Faults	Av. Max. Lat. Displ.
(Wellman, 1953):	(ft)
Wairau Fault	320
Awatere Fault	300
(Lensen, unpublished):	
Clarence Fault	250
Kekerengu Fault	50

North Island Faults	Av. Max. Lat. Displ.
(Lensen, *et al.*, 1956):	(ft)
Owhariu Faault	50
Wellington Fault	250
West Wairarapa Fault	310
East Wairarapa Fault	40

As the average maximum lateral displacements do not change over considerable distanaces (200 miles and more) it can be expected that over a distance of 30 miles, the width of Cook Strait, these displacements remain constant. The average displacements across Cook Strait are correlated to give the pattern shown in Fig. 1. The Awatere Fault (300 ft) bifurcates in Cook Strait to form the Owhariu Fault (50 ft) and the Wellington Fault (250 ft). The Clarence Fault (250 ft) and the Kekerengu Fault (50 ft) join to form the West Wairarapa Fault (310 ft). The other faults in the South Island cannot by this method be correlated with faults in the North Island as not enough is, as yet, known about these faults.

Applying this method, the pattern shown was first determined in 1955 by the author, who has since found that the West Wairarapa Fault branches south-westwards and that the main branch of the West Wairarapa Fault continues through the Orongorongo Range. The trace runs along the Wairongomai River, through the saddle between this river and the Orongorongo River, and is marked by shutter-ridges in the headwaters of the latter river. The discovery of this branch fault strengthens the suggested link between the Clarence and Kekerengu faults and the West Wairarapa Fault.

CORRELATION BY DISTRIBUTION OF EPICENTRES

The method of linking the faults across Cook Strait, by plotting epicentres, has been attempted several times without definite results.

Generally the epicentres are classified in 4 groups, A, B, C, and D, with accuracies respectively of 5, 10, 15, and > 15 miles spread. As more than two-thirds of the epicentres in Cook Strait fall into groups C and D (Mr G. A. Eiby, pers. comm.), this spread allowed considerable latitude in plotting the concealed faults, and, as half of the C

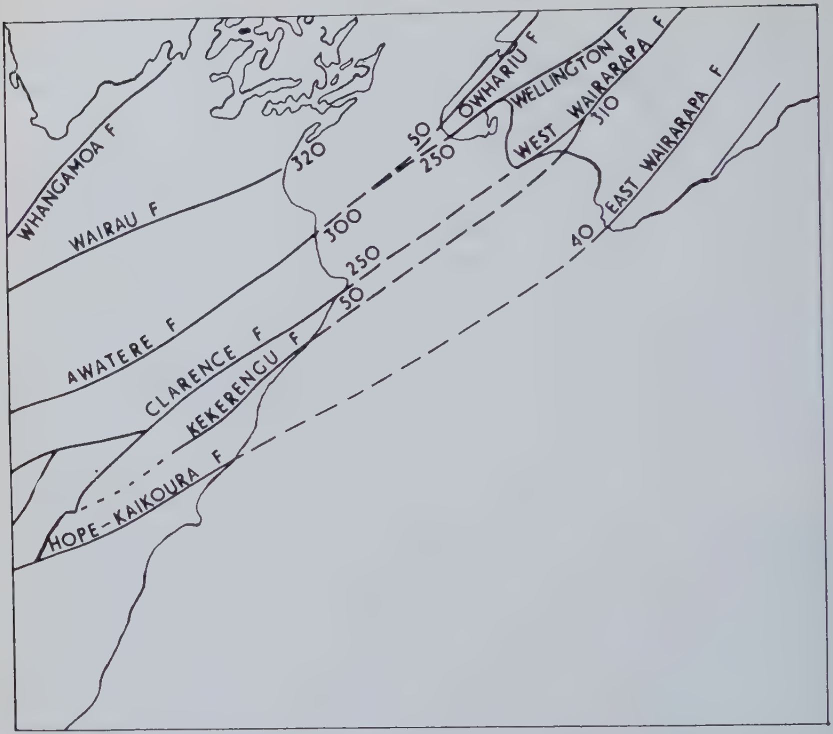

Fig. 1.—Fault Correlations across Cook Strait by Magnitude of Lateral Displacement.

group and the entire D group of epicentres were based on less reliable data, latitude in plotting a fault pattern was further increased.

Recent, as yet unpublished, work by Mr Eiby (pers. comm.) eliminates all epicentres based on insufficient or dubious data and his pruned map shows reliable epicentres to a depth of 40 km. Superposition of this map on the North and South Island fault maps (Fig. 2) demonstrates that in both islands there is a remarkable concentration of epicentres along the faults, and all but one of the clusters of epicentres can be attributed to known active faults. The exception is in the Sounds area, where, although old faults are known, no recent displacements have been found.

In the Cook Strait area the correlation of data allows only one way to link the Hope–Kaikoura Fault with a North Island fault (Fig. 2 E–I). The fact that there are belts without seismic activity on both sides of this alignment, tends to accentuate the alignment between the non-active belts. If this link is accepted, the other links follow without difficulty. The only epicentre that does not seem to fit is that near

Wellington Harbour entrance, which could be attributed to movement on the Baring Head Fault (not shown).

It is also possible to draw lines through epicentres in Cook Strait at approximately a right-angle to the suggested links, but when these alignments are extended on land, they do not coincide with any known active faults.

CONCLUSION

The fault patterns derived from the two methods described are practically identical, and thus support the suggested correlation: additional data may, however, confirm or suggest some modification of this pattern in the future.

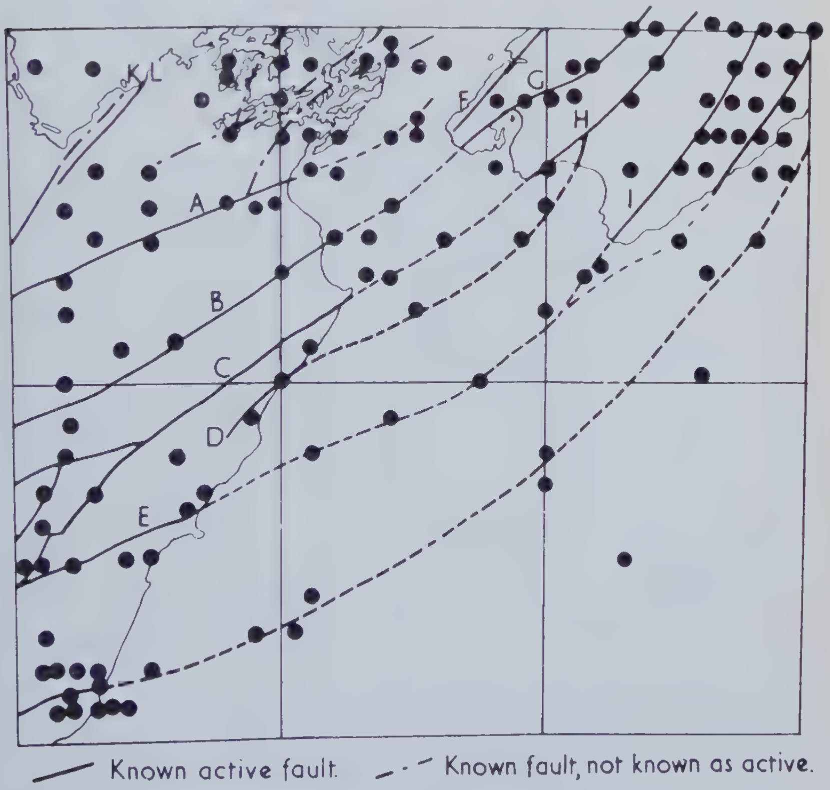

FIG. 2.—Fault Correlations across Cook Strait by Distribution of Epicentres. A: Wairau Fault; B: Awatere Fault; C: Clarence Fault; D: Kekerengu Fault; E. Hope-Kaikoura Fault; F: Owhariu Fault; G: Wellington Fault; H: West Wairarapa Fault; I: East Wairarapa Fault; K: Eighty-Eight Fault; L: Whangamoa Fault.

ACKNOWLEDGEMENT

The author wishes to thank Mr G. A. Eiby of the Seismological Observatory for making available his unpublished map of epicentres of 0 to 40 km, depth.

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POSSIBLE ORIGIN OF PIERCEMENT STRUCTURES, LOCAL UNCONFORMITIES, AND SECONDARY BASINS IN THE EASTERN GEOSYNCLINE, NEW ZEALAND

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Summary

Piercement structures, local unconformities, and secondary sedimentary basins observed in the Eastern Geosyncline are often closely associated with transcurrent fault-zones. Spasmodic and uneven transcurrent movement along these fault-zones is thought to be responsible for the features. Their probable development is shown diagrammatically.

Introduction

Additional, local movements occurred in the Eastern Geosyncline of New Zealand (Macpherson, 1946), during its formation by regional downwarping. The downward movements locally accelerated the deepening of the geosyncline and produced basins, now represented by thick sequences; upward movements locally prevented deepening, and produced highs, which are represented now by unconformities in the sequence of sediments. The association of these structures with transcurrent fault-zones has been observed at several places, notably between the Wairarapa and Palliser fault-zones (Ongley, 1935; Lillie, 1953; Kingma, 1957b).

The author's explanation of this association, and of the formation of the features, is illustrated by simplified diagrams (Figs 1, 2). In the field the structures are usually more complicated, because of syndepositional slumping of sediments from highs, and additional tectonic disturbances.

Basins

Rapid facies changes and thickening of sedimentary sequences over short distances have been observed in the Mapiri, Tutamoe, and Ihungia formations in the Eastern Geosyncline, particularly where the rocks show graded bedding. Such anomalous sedimentation complicates the geology of the area, and makes correlation of beds difficult. The sedimentary sequences in these areas show that throughout the Tertiary there existed small, local basins in which sedimentation was far more rapid than in the Eastern Geosyncline as a whole.

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One such basin, described by the author (1958) and termed a geosynclinette, is typical of many. Because these basins are small, the history of sedimentation in them can be easily traced. The basins may be 15 to 20 miles long by 6 to 10 miles wide, and their sediments may reach a thickness of 15,000 ft. They have been large enough to act as obstacles in the regional folding, and although they have been tilted they have rarely suffered internal folding.

The structural environments of geosynclinettes are well known. Where so far observed they lie either between two systems of parallel transcurrent faults, or along single transcurrent fault-zones. They are particularly common where fault-zones peter out.

PIERCEMENT STRUCTURES

Large isolated blocks of old sedimentary rocks, in some instances several miles long, and bounded on all sides by faults, have been recognized (Lillie, 1953; Ongley, 1935) among the younger deposits of the Eastern Geosyncline, and the writer advances the hypothesis that these horst-like blocks have pierced the younger beds. From Hawke Bay southward these piercements coincide in some places with the cores of anticlines, but like the basins, they are commonly associated with transcurrent fault-zones. It seems that there is some casual relation between transcurrent faulting and the differential elevation of troughs and highs.

Two types of piercement structure may be recognized: (1) those that lie along a single fault-zone; they are usually very much longer than wide (Fig. 1. B. C), and the fault planes that border them tend to be very steep. The faults probably converge and merge downward (Kingma, 1957a). (2) Those that lie between a pair of transcurrent fault-zones; they are invariably very much larger than the first group and may possibly develop into mountain ranges.

Many piercements have been completely eroded and wave cut before becoming involved in wide geosynclinal subsidence and being buried beneath sediments. Local unconformities have thus been created. These local unconformities may represent breaks in deposition at any time between Cretaceous and Pliocene. Oligocene, Miocene, or Pliocene strata may for instance lie on Cretaceous, or Upper Oligocene on lower Eocene. The presence of these unconformities of different ages indicates that piercement bodies were elevated at many different times during the Cenozoic.

TRANSCURRENT FAULTS

Some of these fault-zones can be traced through the eastern North Island as far as Hawke Bay. They are up to a mile in width, and evidence of transcurrent movement has been observed on them by the

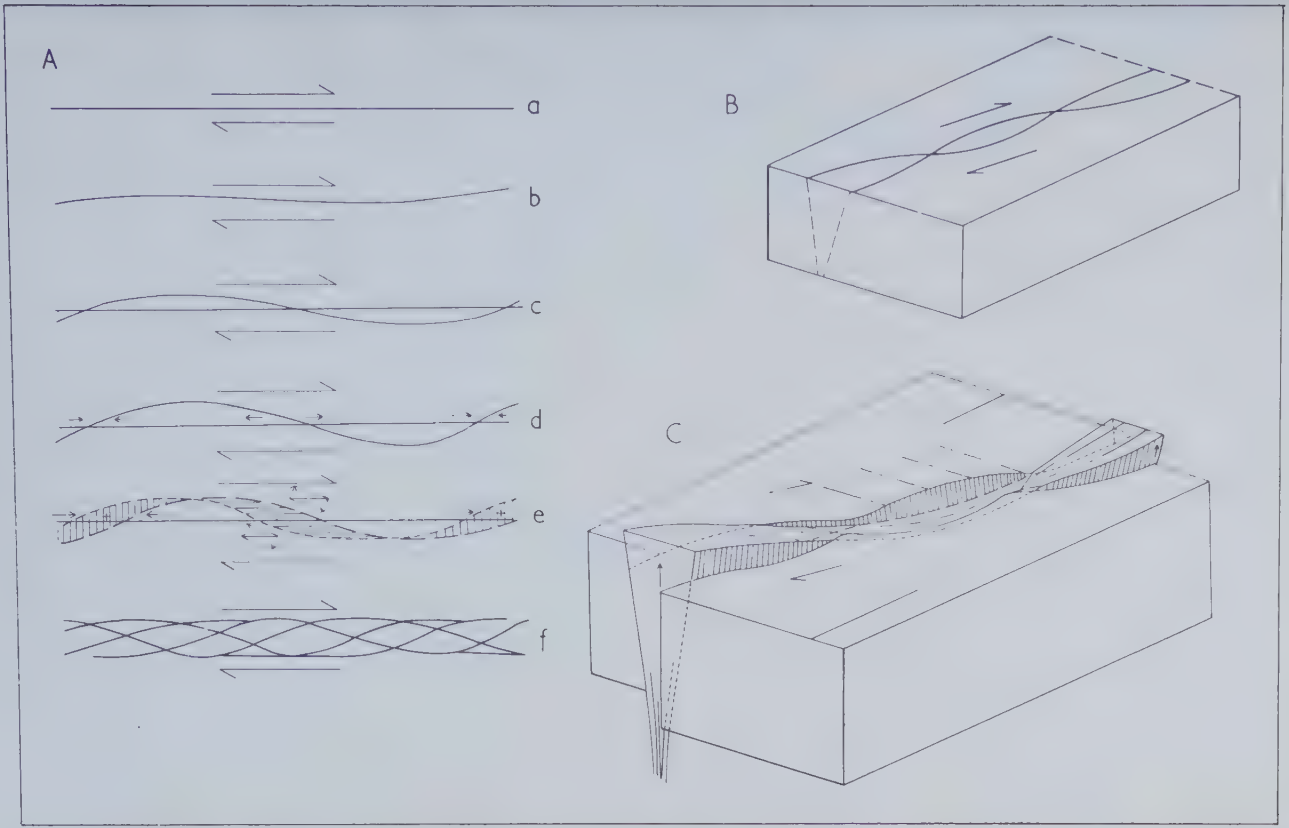

FIG. 1.—A. Stages in deformation and in change of direction along part of a dextral transcurrent fault; — denotes tensional and sinking areas; + compressional and rising areas. B. Dextral transcurrent fault-zone before movement. C. same fault-zone after movement has taken place; development of horsts and graben.

author in the field, and has been deduced from study of aerial photographs by Mr G. J. Lensen (pers. comm. *in* Kingma, 1957b).

En-echelon faulting is common in the fault-zones, which are rarely straight for great distances but have an undulatory course. Some of the en-echelon faults peter out within the fault-zone, the transcurrent movement along individual faults then being taken over by successive members of the echelon (Lillie, 1953; Ongley, 1935). Sometimes a whole zone peters out, and the transcurrent movement then apparently shifts to a neighbouring fault-zone.

There has been argument about the way these faults behave in depth, but from the general wedge shape of the piercement bodies the author believes that the fault-zones converge downwards and merge into a single crush-zone.

RELATIONSHIP OF BASINS AND PIERCEMENT BODIES TO TRANSCURRENT FAULTING

In Fig. 1 A, the development of a transcurrent crush-zone from an originally straight, transcurrent fault is illustrated (the curvature of the faults is exaggerated for emphasis). It is argued that with an originally straight, transcurrent fault, any differences in lithology on opposite sides of the fault will give rise to frictional differences and uneven movements along the fault plane. The original, linear fault will in places change direction because of this friction, and undulations and widening of the zone will result (Figs. 1 A, a–f). With continued movement along an undulating fault (Fig. 1 A, e), alternating areas of tension and compression must result, and corresponding to these sinking and rising areas are created—that is, small lensoid grabens and horsts, or fault angle depressions and tilted blocks (Fig. 1 B, C).

When these horsts emerge as narrow reefs in the geosynclinal seas they will be eroded, and local conglomerates will become incorporated in the marine sequence, thus greatly complicating the regional paleogeographic picture. Such local intraformational conglomerates are encountered at many horizons throughout the Tertiary of the Eastern Geosyncline (Lillie, 1953; Ongley, 1935; Waterhouse and Bradley, 1957). On continued movement past the stage illustrated in Fig. 1 A, e, it is possible that another fault will be initiated and that this in turn may adopt an undulation. If the newer undulations are appreciably offset from the earlier, then it becomes possible for the original horsts to subside and for the basins to be everted. In a transcurrent fault-zone, therefore, large and small blocks can move up and down individually and thus cause radical changes in lithology in place and time.

Much larger basins and horsts, arranged in a different pattern, are formed between widely spaced transcurrent faults. Zones of compression and tension are formed where faults are more than eight miles apart, and particularly where one fault terminates or changes direction,

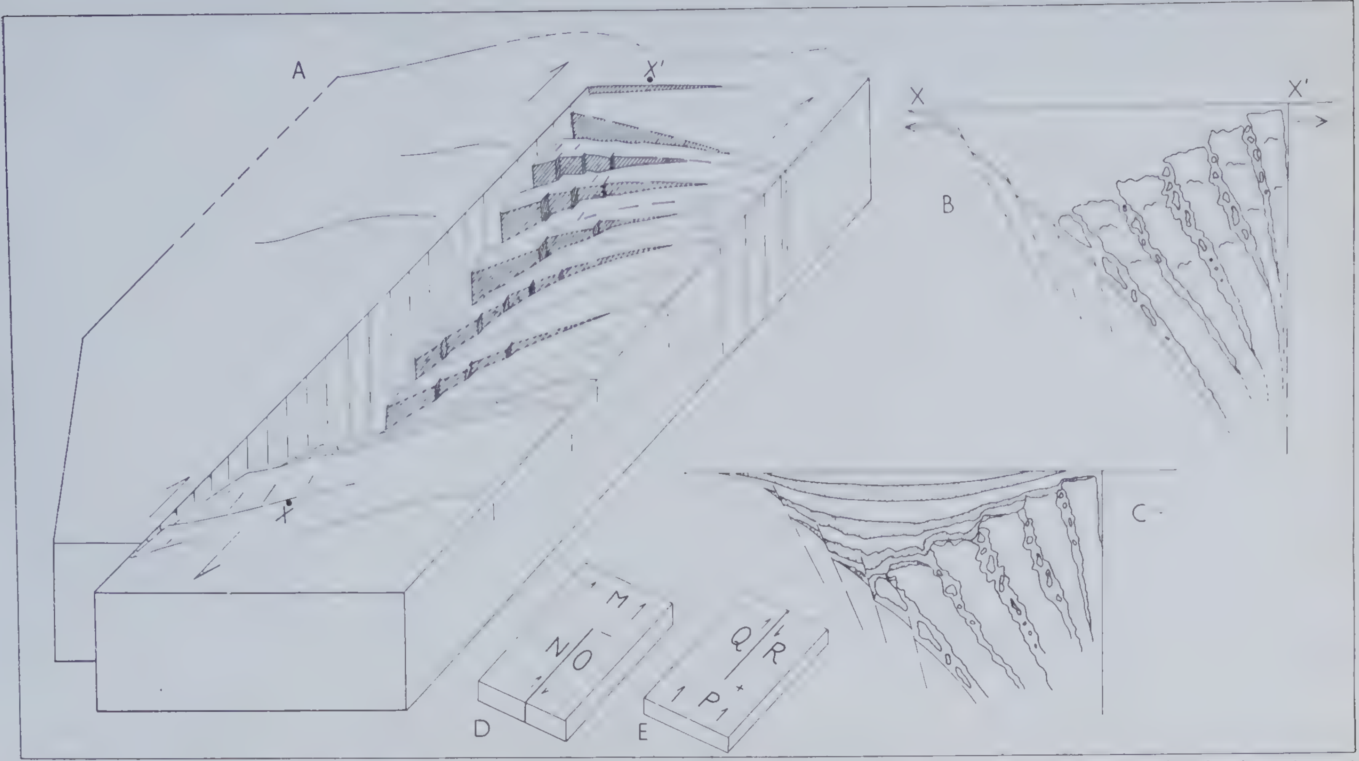

FIG. 2.—A. Dextral transcurrent fault petering out, area to right under tension with consequent collapse. B. Section through collapsed area in A, drawn between points X–X', showing tectonic deformation and breaking up of local "undermass". (Syntectonic sediment cover taken off.) C. Syn-tectonic sedimentary cover restored over broken "undermass". D. Dextral transcurrent fault petering out; — denotes tensional area. E. Dextral transcurrent fault beginning; + denotes rising area.

In Fig. 2 A a subsiding area is shown lying along a fault-zone which is dying out. The area beyond the end of the fault-zone (M) is not broken by transcurrent faulting, and consequently behaves as a unit.

In the area influenced by the fault, block movement takes place between N and O; block O moves away from M, causing tension, and consequently subsidence (Fig. 2 A, D). The opposite case is also possible when a transcurrent fault starts, as illustrated in Fig. 2 E, and an elevation develops between blocks P and R, instead of a depression. When subsidence or emergence takes place locally during geosynclinal sedimentation there is immediate response of facies, and the sedimentary sequence may become much thicker than in the surrounding area, or it may become much thinner, and unconformities may develop.

ACKNOWLEDGEMENT

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THE GEOLOGY OF THE ATIAMURI DAM SITE

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(Received for publication, 19 March 1958)

Summary

The Atiamuri hydro-electric power-station is founded on the summit of a dome of vertically banded Patetere Rhyolite buried beneath rhyolitic pumice breccias and fluviatile sands and gravels. Hydrothermal solutions silicified part of the rhyolite and altered and silicified portions of the pumice breccias near the dam site.

Of three prominent terrace systems the highest (R.L. 910 ft)* is correlated with the Hinuera terrace at Karapiro, and the second (R.L. 860 ft) results from aggradation due to pumice eruptions in the Taupo area about 130 A.D.

Dam and power-house sites were selected after suitable foundations had been proved in a narrow section of the river valley that was free from major leakage channels which would be uneconomic to seal. A leakage channel on the left bank was examined and two suspected leakage channels on the right bank were disproved. A low water-table near river level extends across the dam area and indicates permeable rocks on the left bank.

INTRODUCTION

Atiamuri is a small sawmilling settlement beside the Waikato River about 25 miles south-west of Rotorua on the Tirau-Wairakei State Highway, which crosses the Waikato River about half a mile west-south-west from the site of the new hydro-electric station.

Previous observers include Bidwill (1841), Hochstetter (1867), and Cussen (1889), but the most important survey was by Grange (1937), whose geological map of the Atiamuri Survey District includes the dam site. Modriniak (1951) inferred the presence of a magnetic, dome shaped body from magnetic and seismic surveys for hydro investigations.

PHYSIOGRAPHY

Grange (1937, Plate II) presented a block diagram of the Rotorua district. Near Atiamuri the major physiographic unit is a dissected plateau of ignimbrite and breccia about 1,500 ft above sea-level. Above this plateau rhyolite domes rise prominently almost 1,000 ft.

Upstream from Atiamuri the Waikato River flows in a wide valley in a north-west to west direction to near the junction of the Whanga-

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*R.L. = Reduced Level, which is a level above sea-level in terms of Maraetai Datum. It is believed that the R.L. values are between 7 ft and 8 ft too high.

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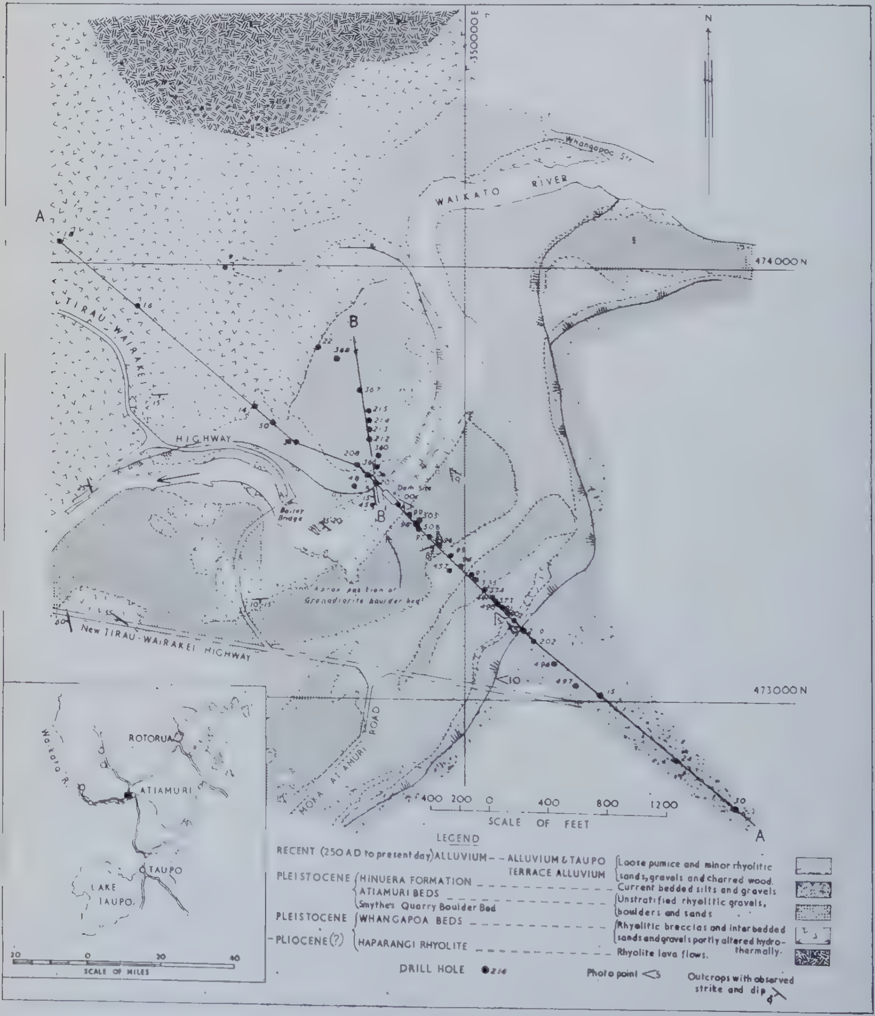
poa Stream, and then in a south-west direction for about 5 miles past the dam site, in a narrow valley between the rhyolite domes Ngautuku on the right bank and Pukeahua on the left bank. The river then turns west and the valley widens.

The river at Atiamuri has three well defined terraces—the highest at 910 ft on both banks, a less prominent one at 860 ft on the right bank, and the lowest at 830 ft on the left bank in which the river is now entrenched. At the dam site the river flows (at about R.L.


350000 E
N
Whangapoa Str.
WAIKATO RIVER
474000 N
473000 N
A
B
B
A
TIRAU-WAIRAKEI HIGHWAY
Bailey Bridge
Dam Site
Approx position of Granodiorite boulder bed
New TIRAU-WAIRAKEI HIGHWAY
MOKA ATIAMURI ROAD
400 200 0 400 800 1200
SCALE OF FEET
Waikato R.
ROTORUA
ATIAMURI
TAUPO
LAKE TAUPO
20 0 20 40
SCALE OF MILES
LEGEND
RECENT (250 AD to present day) ALLUVIUM – – ALLUVIUM & TAUPO TERRACE ALLUVIUM
Loose pumice and minor rhyolitic sands, gravels and charred wood.
PLEISTOCENE HINUERA FORMATION – Current bedded silts and gravels
ATIAMURI BEDS
Smythes Quarry Boulder Bed – Unstratified rhyolitic gravels, boulders and sands
PLEISTOCENE WHANGAPOA BEDS – Rhyolitic breccias and interbedded sands and gravels partly altered hydrothermally.
– PLIOCENE (?) HAPARANGI RHYOLITE – Rhyolite lava flows.
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Outcrops with observed strike and dip

FIG. 1.—Geological map of Atiamuri Dam site.

760 ft) in a narrow channel 100 ft wide between steep banks 50 ft high on the left bank, and 100 ft high on the right bank.

The rhyolite domes Ngautuku (2,054 ft), Pukeahua (2,347 ft), and Pohaturoa (1,705 ft), one mile downstream from Atiamuri, dominate the landscape around the dam site. The largest, Pukeahua, whose highest point is 3⅕ miles south-south-west of Atiamuri, is a flattish dome extending to within 1 mile of Atiamuri. Ngautuku, 1¼ miles north-north-west of Atiamuri, is formed of two coalescing domes of which the southern (altitude 1,840 ft) is the smaller and lower. Pohaturoa is a volcanic neck.

STRATIGRAPHY

General

Atiamuri is near the centre of the central North Island volcanic plateau, over which vast quantities of volcanic material, chiefly rhyolitic, were erupted during the Pliocene and Pleistocene. The pre-Pliocene sedimentary rocks were completely covered and have not been re-exposed by erosion. Following the main eruptions the Waikato River became entrenched in the volcanic rocks. Two late volcanic eruptions in the Taupo area caused aggradation of the river at Atiamuri; between the eruptions and since them the river has cut down in this alluvium.

Thus, at Atiamuri the rocks fall into two main groups: the older volcanic lavas and pyroclastics, and the younger, fluviatile silts, sands, gravels, and boulders. The generalized surface geology of the area is shown in Fig. 1. Geological sections A–A′, B–B′ (Fig. 1) are presented in Fig. 2.

As a result of intensive drilling, and dam site investigations, the subsurface stratigraphy of the area is known in greater detail. Table 1 summarizes the stratigraphy.

Patetere Rhyolite

Content and Distribution

The oldest rocks recognized at Atiamuri are rhyolites correlated with the Patetere Rhyolite of Grange (1937). These rocks do not crop out at the surface but were first encountered in drilling and were later exposed during excavations for the power house and diversion race. Magnetic evidence (Modriniak, 1951) indicated the probable extent, and dome shape of this body of rock.

The rhyolite is light grey, lithoidal, and markedly banded, and has a surface layer approximately 30 ft thick of blocky, slightly vesicular obsidian. Rhyolite flow breccias containing angular inclusions of medium grey rhyolite up to 2 ft diameter, in a shattered brown glassy matrix,

TABLE 1.—Composite Geological Column—Atiamuri Dam Site.

AGE	FORMATION	MEMBER	THICKNESS (ft)	DEPOSITS	ENVIRONMENT
	Alluvium		20 +	Loose pumice and rhyolite sands and gravels.	Fluviatile
				UNCONFORMITY	
130 A.D.	Taupo Terrace Alluvium		90 +	Loose pumice sands and gravels containing fragments of charred wood at base, and pumice sands and silts.	Fluviatile and lacustrine
				UNCONFORMITY	
	Volcanic Ash	Taupo Lapilli Member Rotongaio Ash Member Hatepe Lapilli Member Tirau Ash Member	5 to 20	White and reddish brown volcanic ash.	Subaerial
				UNCONFORMITY	
PLEISTOCENE	*Hinuera Formation		90	Loosely consolidated, current bedded silts, sands, and gravels.	Fluviatile
				UNCONFORMITY	
	Atiamuri Beds	*Smythe's Quarry Boulder Member	45	Loosely consolidated, unstratified rhyolitic boulders chaotically distributed in a fairly loose matrix of sands and gravels.	Lahar
				UNCONFORMITY	
		Gravel Member	40	Fairly well consolidated, rhyolitic and greywacke gravels.	Fluviatile
				UNCONFORMITY	
		Chalazoidite Pebble Member	20	Poorly compacted chalazoidite and rhyolitic pebbles.	Fluviatile
				UNCONFORMITY	
		Chalazoiditic Pumice Breccia Member	46 +	Moderately consolidated, fine rhyolitic breccias with chalazoidites at base, and basal chalazoiditic tuffs.	Subaerial-subaqueous (?); volcanic
				UNCONFORMITY	
		Rhyolitic Sand and Gravel Member	40 +	Poorly consolidated rhyolitic sands and gravels.	Fluviatile
				SEQUENCE UNCERTAIN	
	Atiamuri Granodiorite Boulder Bed			Coarse boulders of rhyolite and granodiorite, poorly cemented.	Fluviatile

			UNCONFORMITY	
Pleistocene	*Whangapoa Beds	200 +	Rhyolitic breccias and interbedded sands and gravels, hydrothermally altered and silicified near top.	Subaerial-subaqueous; volcanic
			SEQUENCE UNCERTAIN	
Pliocene (?)	*Haparangi Rhyolite	?	Rhyolite lava flows.	Subaerial volcanic
			SEQUENCE UNCERTAIN	
	Dome Sandstone	25 +	Compacted, hydrothermally altered rhyolitic sands and silts.	Fluviatile
			UNCONFORMITY	
Pliocene (?)	Patetere Rhyolite	?	Rhyolite lava flows.	Subaerial volcanic

*Units shown on geological map.

were exposed during excavations in the right abutment. Flow breccias containing rhyolite inclusions up to 6 inches diameter were cored in at least 8 holes. The matrix of the flow breccias is brown glass, and bands of scoriaceous and slightly vesicular rhyolite lie parallel to the flow banding. The bulk of the Patetere Rhyolite explored by drilling is banded, light to medium grey, lithoidal rhyolite, containing aligned plagioclase phenocrysts and minor ferromagnesian minerals in a massive, fine-grained matrix. The flow bands are usually between $\frac{1}{4}$ in. and 2 in. wide, but are often fine, about $\frac{1}{8}$ in. wide. They strike between 120° and 170°, dip steeply between 60° E and 70° W, and control the internal structures of the rhyolite. The major joints, the glassy zones, and the alignment of feldspar phenocrysts and matrix material are all parallel to the flow banding.

Minor joint systems consist of one vertical set striking at 85° to 105°, i.e., at right-angles to the flow bands, and a second set with dips of 20° to 65° S, which strikes between 90° and 125°. The bulk of the joints are open and rust-stained, the remainder being filled with secondary silica, or, near the dome surface, with clay. In the more open joints quartz crystals partly fill geodes. Because the joints are open the rhyolite is permeable and hydrothermal solutions have been able to alter part of the rhyolite at the crest of the dome near the Waikato River.

Modriniak (1951) suggested that the "dimensions and general shape of the rhyolite dome at depth should correspond with the magnetic contours", which show an oval pattern elongated towards 120°. Part of the buried surface of the rhyolite is shown in section along the dam centre line in Fig. 2, and by contours in Fig. 3. The levels were obtained from drill-hole information and from exposures made during excavation. The dome is oval in shape, elongated towards 130°, with the highest point on the left bank within 2 chains of the river.

In the Rotorua-Taupo area flows are less numerous than domes, and the Atiamuri rhyolite shows typical vertical flow banding without evidence of lateral flow.

As obsidian and scoriaceous blocks are scarce on the surface of the dome, and the glassy banded rhyolite grades into lithoidal banded rhyolite within about 30 ft, the loose surface blocks were presumably removed by erosion before the overlying sediments were deposited. The scarcity of loose blocks might also be taken as evidence for intrusion, but the field evidence is not conclusive.

Thickness and Relation to Underlying Beds

The total thickness of the rhyolite is unknown, for the base is not exposed and was not reached by drilling. The rhyolite is presumably intrusive into older unknown sediments.

Age and Correlation

No evidence of age is available at Atiamuri. Grange (1937) mapped Patetere Rhyolite as Pliocene. Recent evidence (Fleming & Steiner, 1951) suggests that contemporary volcanism in the central North Island commenced in the late Pliocene.

Dome Sandstone

Content and Distribution

In holes 96, 208, 38, 360, 212-215, and 148, hydrothermally altered sandstone and siltstone, containing occasional large rhyolite boulders, overlie the rhyolite dome. The sandstone is light grey, and contains rhyolite and hydrothermally altered pumice fragments less than $\frac{1}{4}$ in. across, and rhyolitic glass fragments less than $\frac{1}{16}$ in. across, in a matrix of similar, but finer grained, material. A thin, dark grey, silty sandstone, intensely altered hydrothermally, and consisting of angular fragments of flow-banded volcanic rocks, rests directly on the rhyolite in holes 38, 96, and 148. Some of the fragments resemble banded rhyolite. The sandstone in holes 213, 214, 215, and 360 is coarsely bedded, and as it closely resembles the overlying pumice breccias in mineralogical composition, it may be a basal part of the Whangapoa Beds.

The distribution of the Dome Sandstone is known only from drill-hole information. It extends almost to the outer edge of the rhyolite drilled on the right bank, and on the left bank is encountered only in hole 96.

Thickness and Relation to Underlying Beds

The known thickness ranges from 23 ft in hole 96 to 2 ft in hole 38, averaging $7\frac{1}{2}$ ft, but a greater thickness may be preserved beyond the drill-holes. The sandstone appears to have been eroded before the deposition of the Whangapoa Beds.

The Dome Sandstone rests unconformably on Patetere Rhyolite, the only older formation with which it is in contact.

Age

The exact age of the beds is unknown, but is probably late Pliocene or early Pleistocene.

Haparangi Rhyolite

Content and Distribution

The north end of the area is bounded by the steep slopes of Ngautuku, a dome built by successive extrusions of rhyolite. It is surrounded by steep scree slopes, rising to a line of cliffs of banded Haparangi Rhyolite.

The rhyolite is mainly massive with minor flow banding. On the east side of the dome at grid reference N85/503753 the bands are from 2 in. to 6 in. thick, and dip west at about 15°. The rock is slightly scoriaceous and vertically jointed. The rhyolite contains phenocrysts of feldspar, glass, and subordinate spherulites up to $\frac{1}{8}$ in. diameter in a lithoidal to glassy matrix. Mr J. Healy (pers. comm.) reports a coarse pumice breccia at grid reference N85/497741, in which small and large angular fragments of sugary textured pumice are welded to form a homogeneous rock; it is probably a flow breccia.

Thickness and Relation to Underlying Beds

The thickness of the Haparangi Rhyolite and its relation to older formations are unknown.

Age

Grange (1937) mapped Haparangi Rhyolite as late Pliocene–early Pleistocene.

Whangapoa Beds

Distribution and Content

The Whangapoa Beds consist of a light green, rhyolitic pumice breccia and interbedded gravels and sands, partly silicified and hydrothermally altered near the dam site. The most extensive exposure is in the cliff face (type locality N85/498735), on the right bank downstream from the old highway bridge, and in the face of the 910 ft terrace on the left bank.

On the right bank (Fig. 4) the Whangapoa Beds are stratified in layers up to about 10 ft thick, separated by silt layers about 1 ft thick. The breccias are light brown, moderately well compacted, and contain abundant sub-rounded pumice up to 1 in. diameter, in a sand grade pumiceous matrix. The pumice is devitrified and partly altered into chloritic clays in the hydrothermally altered zone. Rhyolite fragments and magnetite occur sparsely, and quartz and a small amount of pyroxene are also present. At grid reference N85/499740 the breccia exposed in the cliff face is massive and poorly stratified. It consists mainly of a matrix of sand grade pumice, rhyolite, and obsidian, with scattered boulders of rhyolite. About 70 ft below the crest there is a poorly defined horizon about 10 ft thick of scattered boulders of granodiorite, diorite, rhyolite, and small angular greywacke pebbles. The granodiorite pebbles are either about 1 in. diameter and fairly common, or about 1 ft diameter and rare; the diorite boulders are about 6 in. diameter and rare, and the rhyolite boulders are up to 4 in. diameter and common. A granodiorite boulder is described by Mr A. Steiner (pers. comm.) as being "of medium grain size with porphyritic

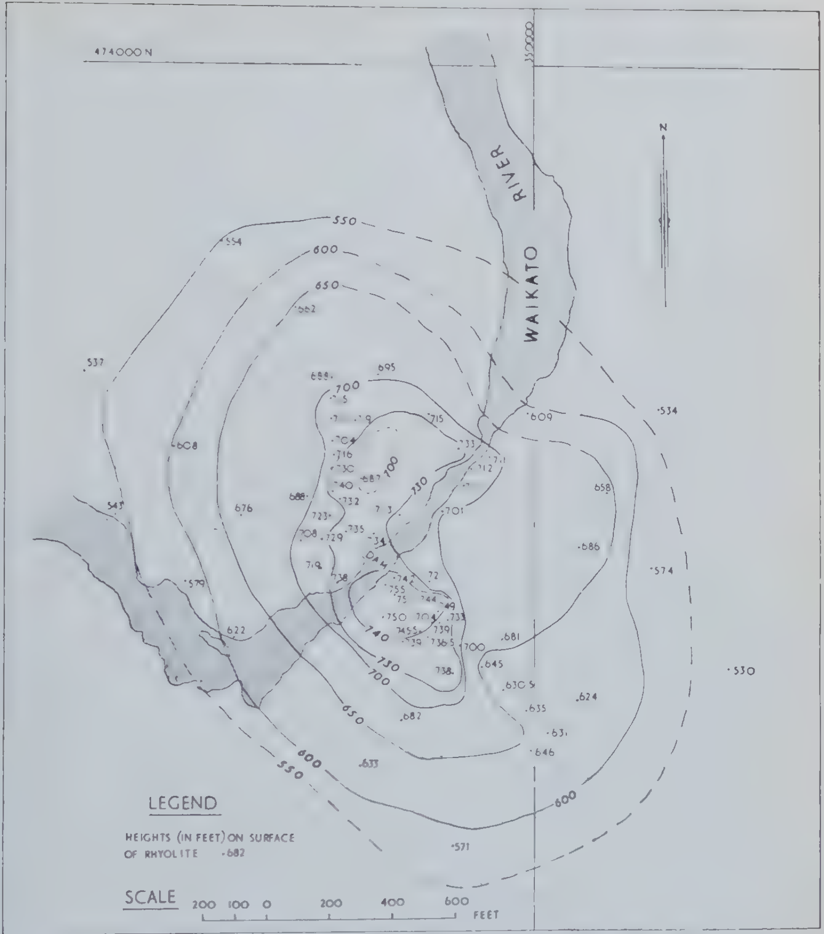

FIG. 3.—Contours on top of buried rhyolite dome.

texture. It consists essentially of large, zoned albite-oligoclase crystals enclosed by smaller grains of myrmekite intergrowths and rounded quartz. A subordinate amount of ferromagnesian minerals is also present, but the amount of potash feldspar is negligible only. The rock appears to be a dyke rock which can be classified as granodiorite or trondhjemite according to Hatch, Wells, & Wells (1949) or as a tonalite in the sense of Nockolds (1954)". The diorite consists "of soda-calc plagioclase, hornblende, and pyroxene, in this order of decreasing abundance. The plagioclase predominates over the ferromagnesians and magnetite is an accessory". Rhyolite pebbles are abundant, the most common types being spherulitic, banded, and

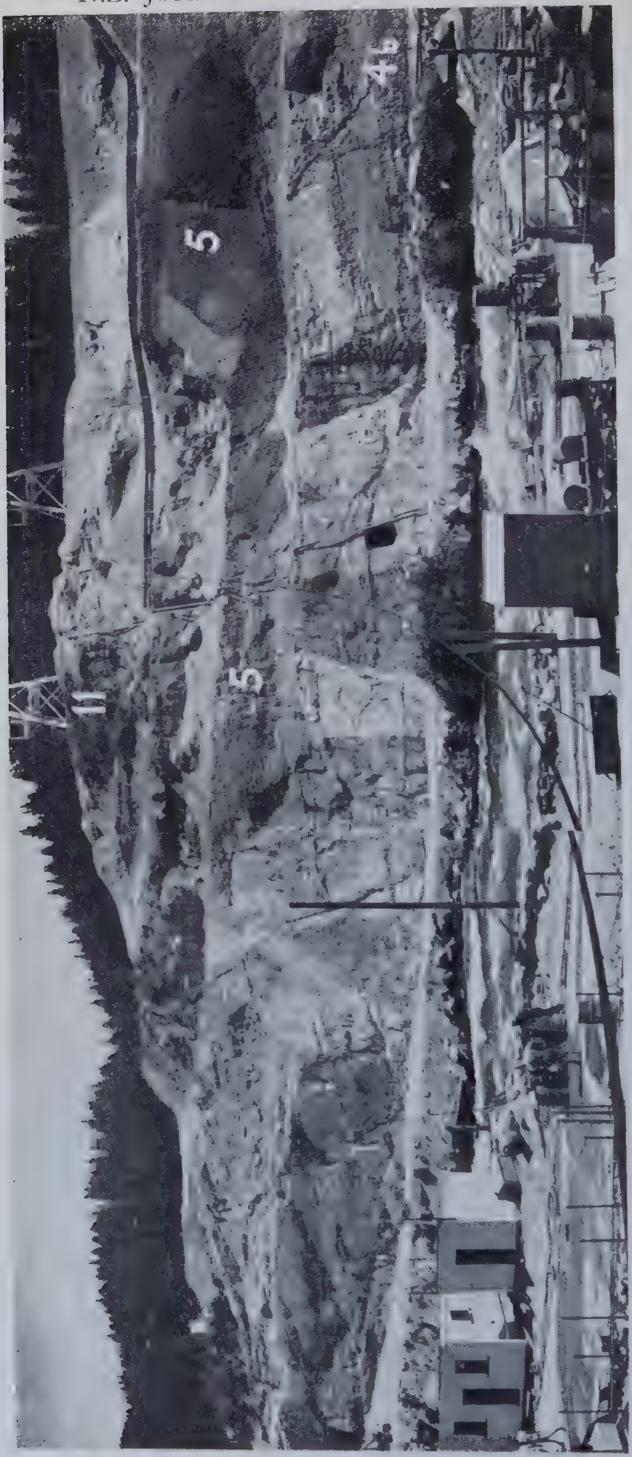

FIG. 4.—Right bank downstream of dam centre line.

11 Hinuera Formation
5 Atiamuri Granodiorite Boulder Bed
4b Whangapoa Beds

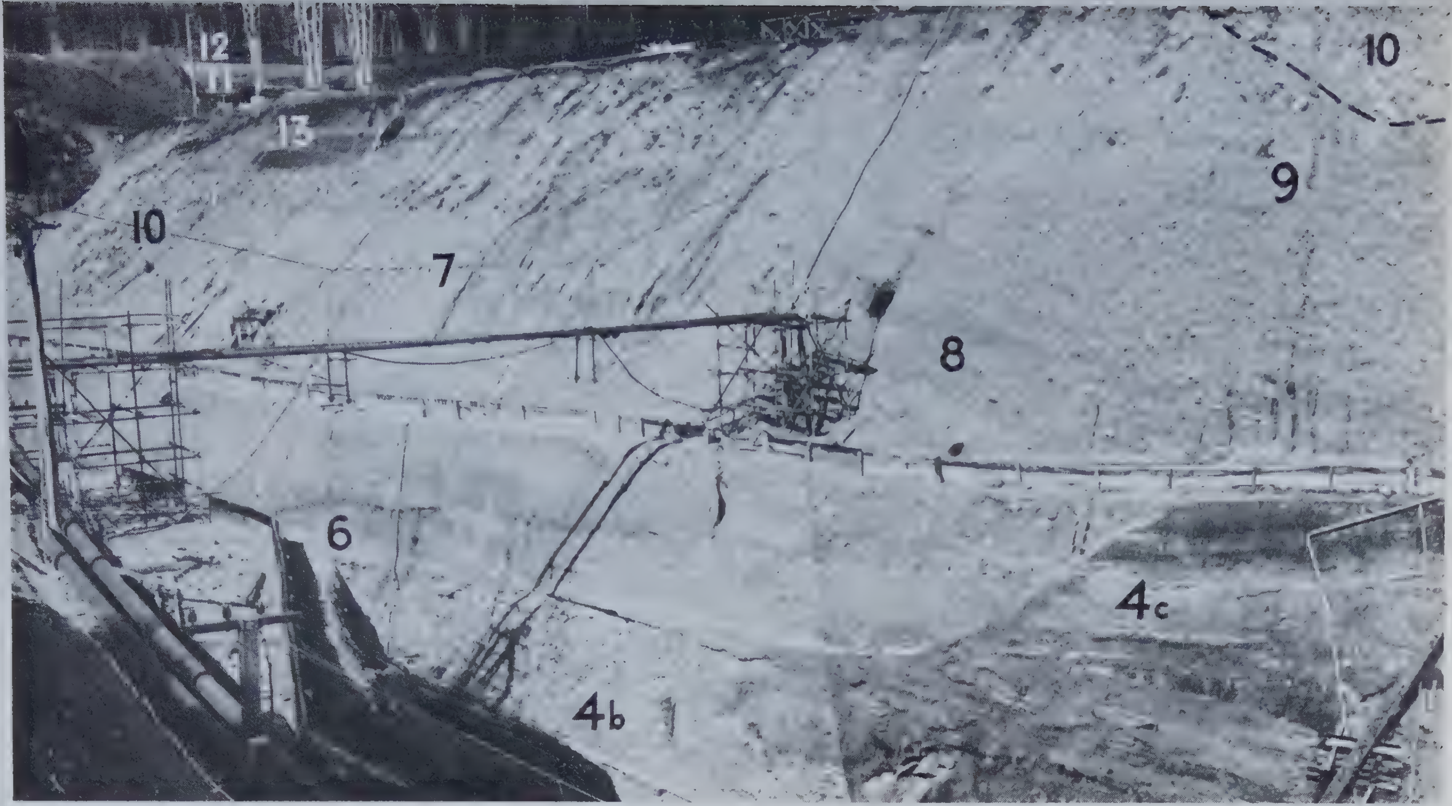

FIG. 5.—Left bank cut-off wall excavation, west face.

13 Taupo Terrace Alluvium
12 Volcanic Ash
11 Hinuera Formation
10 Smythe's Quarry Boulder Member
9 Gravel Member
8 Chalazoidite Pebble Member
7 Chalazoiditic Pumice Breccia Member
6 Rhyolitic Sand and Gravel Member
4 (b, c) Whangapoa Beds

lithoidal, and fairly dense pumice. Highly vesicular pumice is concentrated in layers.

In the left bank diversion cut, the hydrothermally altered pumice breccia consists of a lower, massive, jointed, and silicified green breccia (Fig. 5, 4b), and an upper, stratified breccia containing silt, gravel, and boulder lenses (Fig. 5, 4c). The lower breccia contains inclusions of angular, white to yellow pumice up to 1½ in. diameter, but mostly less than ¼ in. in size, and granules of weathered rhyolite, in a matrix of fine pumiceous glass, crystals of fresh and corroded quartz, oligoclase, andesine, and minor amounts of hypersthene and magnetite. The green cementing material seen in hand specimen is chalcedony. The upper member consists of layers of pumice breccia up to 8 ft thick, separated by gravel and silt layers up to 1 ft thick. The pumice breccia is light grey and contains abundant, subangular fragments of fairly fresh pumice of the Haparangi type. The fragments are up to 3 in. in size, but are mostly less than 1 in. Angular fragments of light and dark grey rhyolite, mostly less than ½ in., but up to 2 in. in size, are fairly common, and there are a small number of chalazoidites up to ¾ in. The gravels contain lenses of sub-rounded to angular, dark to light grey rhyolite up to 2 in., and sugary, pumiceous rhyolite up to 1 ft in size. A few blocks of stratified sinter up to 3 ft in size are scattered along the top of these beds.

At the base of the R.L. 910 ft terrace in the cut-off wall excavation, the larger pumice particles are sorted in some places into layers one particle thick, separated by layers of massive, sand grade, pumiceous matrix up to 1 ft thick (Fig. 6). Between the Bailey bridge and the new main highway bridge the breccia is poorly consolidated and stratified. It is composed of sugary-textured, pumiceous rhyolite fragments mostly less than ¼ in. in size, in a fine-grained matrix of similar material. Boulders of sugary textured, pumiceous rhyolite up to 2 ft, and a block of siltstone 4 ft in diameter, crop out within the breccia in a road cutting 9 chains east of the new main highway bridge. The rhyolite contains phenocrysts of plagioclase, quartz, and hornblende, and is similar to that cropping out at Round Hill (Thompson, *et al.*, 1954). Nearby, the breccia is banded and the bands strike 130° and dip 55° S.S.W. The thicker layers are up to 6 in. and contain angular pumice between ¼ in. and ½ in. and rare lithoidal rhyolite less than 1 in. The narrow bands are up to 1½ in. thick and consist of silt grade pumice. Within 4 chains of the river the bands strike 170° and dip 60° W.

Three prominent sets of intersecting joints or faults traverse the pumice breccia in the right abutment excavation (Fig. 4); the major set strikes at between 60° and 70° and dips between 55° and 80° N.N.W., another set strikes 90°–95° and dips 65°–85° N., and the third set strikes 115°–140° and dips 60°–80° N.E. It is along these joints that hydrothermal alteration and silicification have been most intense in the upper levels of the breccia (Fig. 7).

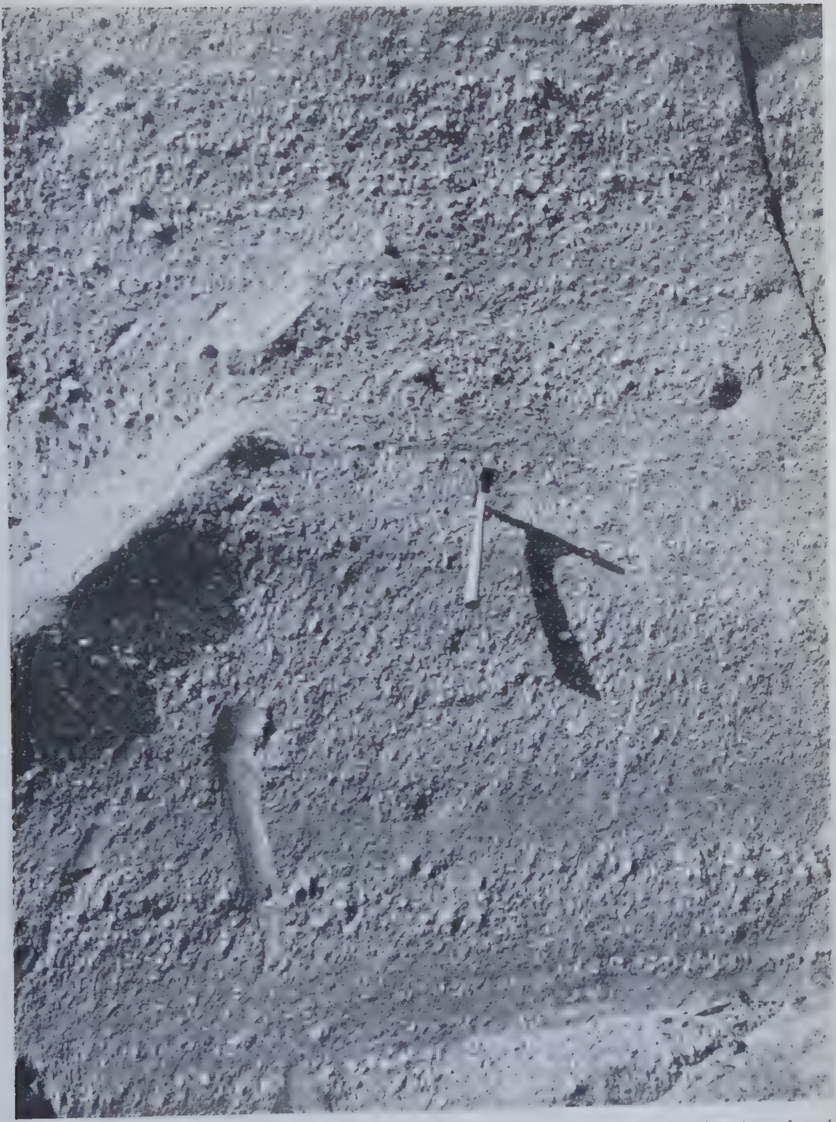

FIG. 6.—Unaltered Whangapoa Beds showing rough sorting of pumice into bands at base 910 ft terrace on dam centre line.

The effects of hydrothermal alteration range from severe leaching with the production of clays, to intense silicification. Silicification is most intense at the base of the breccia near the rapids, and it decreases upwards and laterally. In the left bank terrace (910 ft, Fig. 2) hydro-

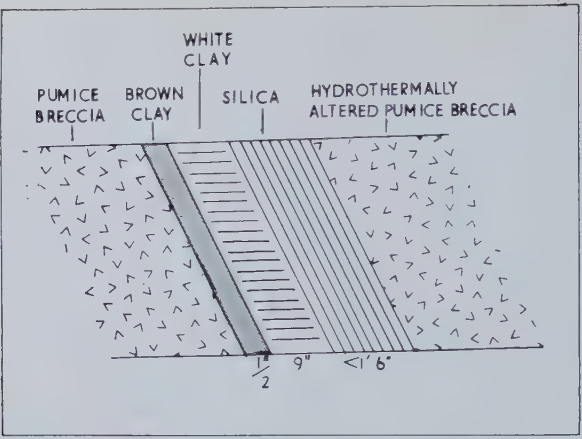

Fig. 7.—Section across silicified joint in Whangapoa Beds, right abutment.

thermally altered pumice breccia up to 110 ft thick overlies unaltered pumice breccia. Hot water rising near the summit of the Patetere Rhyolite dome appears to have moved south-east as a layer on top of the cold ground water and to have altered the pumice breccia within the hot water zone.

In the right abutment excavation, silica veins fill joints and extend along adjacent bedding planes, as shown in the typical section (Fig. 7). The degree of hydrothermal alteration decreases outwards from the silica vein until the altered pumice breccia merges into unaltered pumice breccia. Wherever examined, the clay zone, which rests on the foot wall, is overlain by a silica vein. Above the vein, the pumice breccia is silicified and hydrothermally altered.

Field evidence suggests that the following was the sequence of hydrothermal alteration. As hot water rose up the joints, silica in the pumice breccia on both sides of the joints was leached and the breccia converted to clay. Farther up the joint the silica-rich solutions deposited silica on the hanging wall side, probably as a result of mixing with downward percolating cold ground water. As the hanging wall became more silicified and impermeable, leaching on the foot wall continued until it was either rendered impermeable or hydrothermal action ceased.

Origin of Pumice Breccias

The pumiceous rhyolite fragments closely resemble the pumiceous phase of the Haparangi Rhyolite in texture and mineral content. The fragments would expand if heated to about 1000° C.

Judged solely by the stratification observed in a few outcrops, the upper breccias may have been erupted from a vent on the south-west slopes of Ngautuku. It is suggested that the Haparangi Rhyolite magma, containing excess gas, burst through the sides of Ngautuku and explosively erupted gas-generating avalanches (*nuées ardentes*) of finely comminuted material. These avalanches, carrying fragments of non-cognate rhyolite from the walls of the pipe and vent, together with a few blocks of siltstone and unexpanded magma and boulders of granodiorite, diorite, and greywacke, came to rest at the foot of Ngautuku. The oldest breccias flowed into water, probably a small lake, and were roughly sorted.

Thickness and Relation to Underlying Beds

The thickness of the Whangapoa Beds exceeds 200 ft on the left bank, where drill-holes did not penetrate the thickest section of the breccia.

The Whangapoa Beds unconformably overlie the Patetere Rhyolite. In excavations the contact is irregular and silicified. The contact between the pumice breccia and the Dome Sandstone is disconformable, or possibly unconformable.

Age and Correlation

The age of the Whangapoa Beds is not known definitely, but may be either Pliocene or early Pleistocene. Grange (1937) mapped the pumice breccia between the Waikato River and Ngautuku as Patetere ignimbrite and breccia (Pliocene), but if the breccias were erupted from Ngautuku, a Pliocene or early Pleistocene volcano, they are of Pliocene or Pleistocene age.

The pumice breccias may differ in age within the Pliocene-Pleistocene, but they cannot be separated in the field, and they have been grouped together for mapping purposes. The hydrothermally altered pumice breccia is jointed, probably through earth movements, but the unaltered pumice breccias, especially those downstream from the Bailey bridge, are neither jointed nor altered hydrothermally, and may be younger.

Atiamuri Granodiorite Boulder Bed

Distribution and Content

Excavations for the right abutment (type locality grid reference N85/498735), and for the diversion race on the left bank, exposed an old river channel containing rusty gravels with distinctive granodiorite boulders (Figs 1, 2, and 4). The material forming the channel between these exposures has been eroded by the river, and drilling beyond these points failed to locate granodiorite boulders, although they were encountered in the right abutment cut-off wall drives. (Fig. 2, section

B–B′). Between the two exposures, the base of the bed falls approximately 50 ft in 300 ft in a southerly direction.

The Atiamuri Granodiorite Boulder Bed is unsorted and consists predominantly of rounded boulders of lithoidal rhyolite up to 6 in., and scattered, well rounded boulders of weathered granodiorite up to 2 ft, in a matrix of pumice, glass, quartz, and rhyolite sand, partly cemented by iron oxide.

Thickness and Relation to Underlying Beds

The Atiamuri Granodiorite Boulder Bed is about 20 ft thick on the right bank and about 50 ft thick on the left bank. It rests unconformably on slightly altered and silicified Whangapoa Beds on both banks. Its relation to the Atiamuri Beds is not clear.

Age and Correlation

The Atiamuri Granodiorite Boulder Bed is probably early Pleistocene, as it is overlain by the Hinuera Formation (Pleistocene) and rests on the Whangapoa Beds (Pliocene?–Pleistocene).

Granodiorite is not known to crop out in the North Island, the nearest known being in the Nelson district in the South Island. Apart from the Atiamuri Granodiorite Boulder Bed, the Whangapoa Beds upstream from the dam, and a few granodiorite boulders encountered as inclusions in pumice breccias drilled recently at Huka Falls near Taupo, no other outcrops containing granodiorite boulders are known in the Rotorua-Taupo volcanic area, or in the Waikato River valley. North of Auckland, granodiorite and quartz-diorite boulders are found in the Albany Conglomerate (Bartrum, 1920, p. 425). Park (1893) describes a granite conglomerate in the King Country.

The granodiorite boulders and some of the rhyolite boulders were derived by erosion from Whangapoa Beds containing these rocks as inclusions upstream from grid reference N85/499740. Some of the rhyolite may have been eroded from the flanks of Ngautuku.

Atiamuri Beds

The Atiamuri Beds consist of six members, five of them exposed only in the left bank cut-off wall excavation (grid reference N85/500733, Fig. 5). The other, Smythe's Quarry Boulder Member, is represented by large boulders distributed as a mappable unit along the valley floor from near Atiamuri to downstream of Whakamaru. The members are:

Top .... Smythe's Quarry Boulder Member
Gravel Member
Chalazoidite Pebble Member
Chalazoiditic Pumice Breccia Member
Bottom .... Rhyolitic Sand and Gravel Member

Because little is known of the extent of the members beyond Atiamuri they have been grouped together.

RHYOLITIC GRAVEL AND SAND MEMBER

Distribution and Content

The loosely compacted, current-bedded gravels and sands which constitute this member are exposed only in the left bank cut-off wall (N85/500733, Figs 2, 5, and 8), and rest on the Whangapoa Beds. They are confined to a channel about 350 yards wide, between the right abutment and the left bank 910 ft terrace. Their extension upstream and downstream is unknown.

The gravels consist of pumice, lithoidal rhyolite, and hydrothermally altered and silicified pumice breccia boulders up to 6 in. in size, in a sand matrix of pumice, rhyolite glass, and rhyolite. The silicified pumice breccia resembles that cropping out in the gorge at Ohakuri dam site, 6 miles upstream from Atiamuri.

Current bedded sands and silts rest unconformably on the gravels, and consist of pumice, rhyolitic glass, and rhyolite. The current bedding shows that the water flowed downstream at right-angles to the cut-off wall.

Thickness

In hole 373, where it is thickest, the Rhyolitic Gravel and Sand Member is 53 ft thick.

CHALAZOIDITIC PUMICE BRECCIA MEMBER

Distribution and Content

The Chalazoiditic Pumice Breccia Member is exposed in the left bank cut-off wall (N85/500733); it has not been found in natural outcrops in the dam area.

It consists of two parts, the lower chalazoiditic tuff, and the upper chalazoiditic pumice breccia. The chalazoiditic tuffs (Fig. 8, 7a) are thinly bedded and contain chalazoidites up to 1 in. diameter in a pumiceous tuff matrix. The chalazoidites are rounded or slightly flattened parallel to the bedding, and are concentrated mainly between the beds. The upper surface of the tuffs is eroded.

The chalazoiditic pumice breccia is light green, unbedded, poorly consolidated, and unaltered hydrothermally. It contains minor, subangular rhyolitic pumice up to $\frac{1}{4}$ in., in a sand and silt matrix of rhyolitic fragments. Chalazoidites up to 1 in. diameter are scattered through the basal 5 ft.

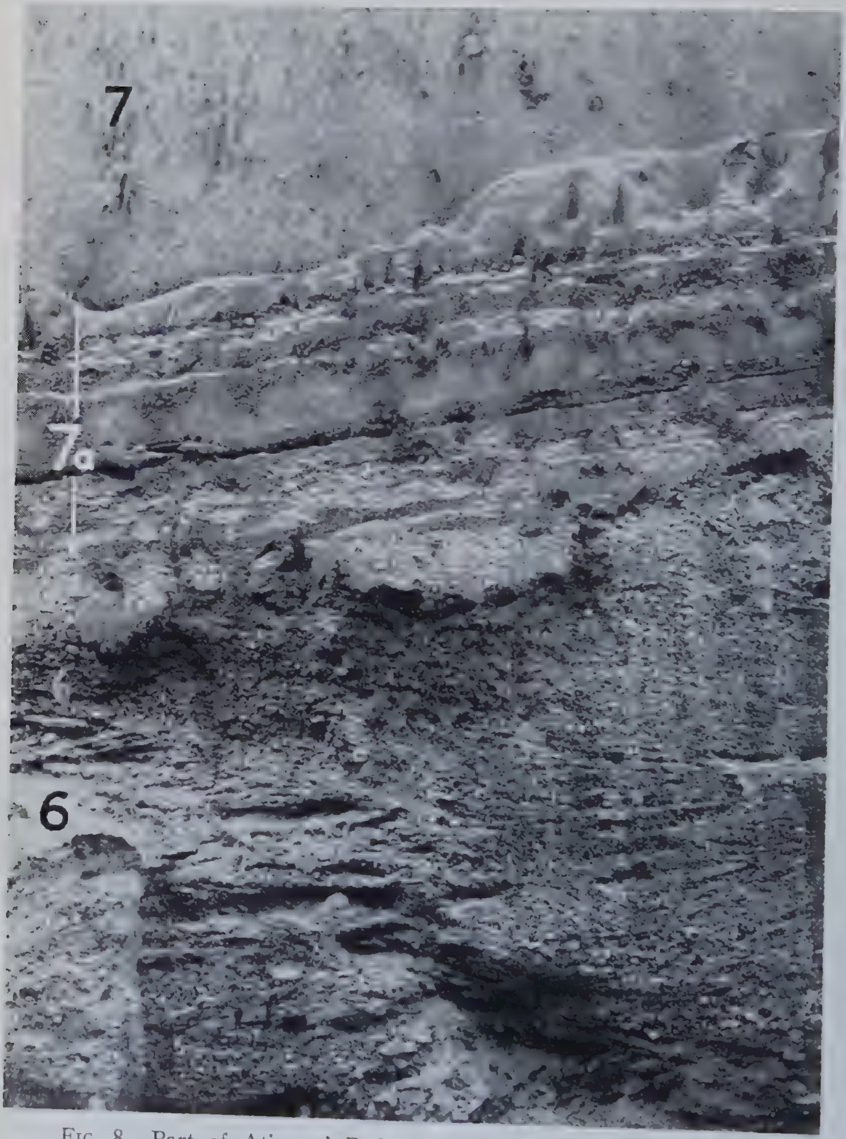

FIG. 8.—Part of Atiamuri Beds exposed in left bank cut-off wall.
7 Chalazoiditic Pumice Breccia Member
7a Chalazoiditic tuffs
6 Rhyolitic Sand and Gravel Member

Origin of Chalazoidites

Marwick (1946) describes chalazoidites from the Te Kuiti district. The methods of formation of chalazoidites have been discussed by

Berry (1928). Two methods of formation appear to have operated at Atiamuri. They are:

(a) aggradation around a nucleus buffeted in an expanding ash cloud before falling to the ground as "volcanic hailstones", and

(b) the "snowballing" of small hailstones, volcanic or ice, rolling down the wet surface of loose volcanic ash.

In (a) the chalazoidites would fall into the advancing avalanche and would be included in unbedded breccia, for example, the Chalazoiditic Pumice Breccia Member in the left bank cut-off wall, or in subaerial ash beds. In (b) the chalazoidites would be concentrated between the beds and not in the beds, for example, in the tuffs at the base of the Chalazoiditic Pumice Breccia (Fig. 8).

Thickness and Relation to Underlying Beds

The chalazoiditic tuffs are up to 2 ft 6 in. thick, and rest unconformably on the Rhyolitic Gravel and Sand Member.

The Chalazoiditic Pumice Breccia Member is thickest (50 ft) in holes 93 and 94, and it rests unconformably on the Rhyolitic Gravel and Sand Member.

CHALAZOIDITE PEBBLE MEMBER

Distribution and Content

The Chalazoidite Pebble Member is exposed only in the left bank cut-off wall, north-west of the Chalazoiditic Pumice Breccia Member; it is not known outside the dam area. It is a massive, loosely compacted aggregate of chalazoidites, rhyolite, and sinter, in a sand matrix of fluviatile origin.

Abundant loose chalazoidites up to 1 in. in size, probably eroded from the base of the Chalazoiditic Pumice Breccia Member, are a distinctive feature of this member. Other small constituents include rounded, white fragments of hydrothermally altered pumice breccia up to 1 in., pale grey, sub-rounded, pumice breccia up to 6 in., and dark grey and black, angular rhyolite up to ¼ in. Large boulders of hydrothermally altered fine pumice breccia up to 2 ft, a block of soft, brown volcanic ash 4 ft in diameter, and minor sinter up to 4 in. are scattered through this member.

Thickness and Relation to Underlying Beds

In the exposed section the Chalazoidite Pebble Member is 20 ft thick. It rests unconformably partly on the Chalazoiditic Pumice Breccia Member, partly on the Sand and Gravel Member, and partly on Whangapoa Beds. It underlies Smythe's Quarry Boulder Member.

GRAVEL MEMBER

Distribution and Content

Like the underlying Chalazoidite Pebble Member, the Gravel Member is known only in the left bank cut-off wall. On the downstream face of the cut, the gravels form a massive, fairly well consolidated deposit, in which the pebbles are sorted into not easily discernible alternating beds, each containing different sized pebbles. The beds are up to 1½ ft thick.

The main constituent of the Gravel Member is rhyolite of various types, including rounded light grey banded, angular dark grey finely banded, and rounded sugary pebbles up to 3 in. diameter but mostly less than 1 in. There are smaller amounts of sub-rounded boulders of light grey lithoidal rhyolite up to 6 in.

Rounded pebbles of dark grey fine sandstone and siltstone grade greywacke up to about 1 in. in size comprise the most distinctive constituent. The largest boulders, which measure up to 1½ ft diameter, consist of hydrothermally altered and silicified pumice breccia containing abundant pumice up to ½ in., and a few chalazoidites in a fine matrix. Angular pebbles of pink sinter less than 6 in., and finely banded siltstone less than 4 in. in size are minor constituents, in a matrix of glass, feldspar, rhyolite, and ferromagnesian minerals down to $\frac{1}{16}$ in.

Thickness and Relation to Underlying Beds

The Gravel Member, 20 ft thick, rests unconformably on Whangapoa Beds, the Chalazoidite Pebble Member, and the Chalazoiditic Pumice Breccia Member. As internal stratigraphic breaks are absent, the gravels represent a period of continuous aggradation of the Waikato River.

SMYTHE'S QUARRY BOULDER MEMBER

Distribution and Content

Between Atiamuri and Whakamaru large boulders are a prominent feature of the Waikato River valley floor. At Atiamuri they are confined to the left bank, where they cover a small area opposite the mouth of the Whangapoa Stream, most of the left bank 830 ft terrace (Figs 5 and 9) at the dam site, and a large area downstream from the Bailey bridge. They are best exposed in the left bank cut-off wall (Fig. 5), and in an incomplete section at Smythe's Quarry on the Whakamaru Road 2½ miles downstream.

The member is loosely consolidated and unstratified, and consists of large rhyolitic boulders chaotically distributed through a loose matrix of finer sands and gravels. Most of the boulders are less than 5 ft in diameter, although there are larger ones up to 30 ft on the terrace surface. The smaller boulders are commonly neither well silicified nor rounded, while the larger are heavily silicified, and sub-rounded to sub-angular. At Smythe's Quarry, blocks of light and dark grey lithoidal rhyolite and sheeted rhyolite up to 20 ft are scattered amidst blocks of green and banded multicoloured pumice breccia.

At Atiamuri the most abundant rock type among the boulders is a silicified and hydrothermally altered pumice breccia, similar to that cropping out in the Ohakuri Gorge, 5 miles upstream. This silicified breccia is multicoloured, light green and brown being the most common colours. Boulders of the softer, unsilicified pumice breccia consist mainly of clays, and rarely exceed 1 ft diameter. Less conspicuous are rounded blocks of light grey Chalazoiditic Pumice Breccia Member up to 3 ft, and occasional, angular, locally derived blocks of layered, pink to white sinter up to 2 ft. There is a notable absence of rhyolite blocks.

Pebbles of rhyolite of several kinds, including sugary, lithoidal, and finely and coarsely vesicular pumice comprise the commonest constituent of the matrix of the Smythe's Quarry Boulder Member. There are also small amounts of rounded, flattened, greywacke pebbles up to about 1 inch in size, sinter pebbles, and pebbles of silicified and hydrothermally altered pumice breccia. The sand of the matrix is made up of pumice, glass, and rhyolite.

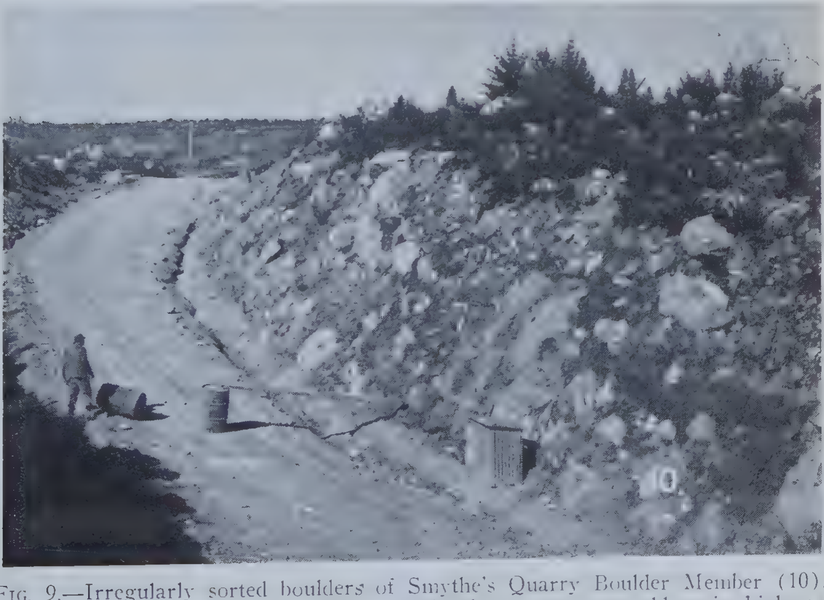

FIG. 9.—Irregularly sorted boulders of Smythe's Quarry Boulder Member (10), which forms part of the left bank 830 ft terrace near old main highway bridge. Terrace in left background is 910 ft terrace of Hinuera Formation (11).

Thickness and Relation to Underlying Beds

In the left bank cut-off wall the boulder member is 15 ft thick on the south-east side of the Chalazoiditic Pumice Breccia Member, 35 ft thick on the north-west side, and almost absent in the central section. Its total thickness is not known, as the base is not exposed.

The unconformable contact with the underlying Gravel Member is not marked by a distinct stratigraphic break, but by an abrupt change in lithology and particle size.

Correlation and Origin

At the dam site the relationship between Smythe's Quarry Boulder Member and the Hinuera Formation is not clear. In Smythe's Quarry the Hinuera Formation overlies the boulder member unconformably.

Because of the unstratified nature of the deposit, the presence in it of large boulders up to 30 ft in diameter and its ribbon-like distribution along the valley floor, Mr Healy (pers. comm.) has suggested for it a lahar origin. Several authors (Williams, 1932; Fenner, 1937) have discussed the ability of mudflows to transport large boulders considerable distances, and have described the resulting chaotic distribution of large and small boulders in a sand or gravel matrix. Similar deposits on the slopes of Mt. Egmont and Mt. Ruapehu (Grange, 1931), and in the Hautapu Valley south-west of Mt Ruapehu (Te Punga, 1953, pp. 32-34), are believed to have originated as lahars. A lahar, the lubricant for which originated in the Crater Lake of Mt Ruapehu, carried boulders up to 5 ft in diameter past the Tangiwai Railway Bridge, destroying part of it on December 24, 1953 (O'Shea, 1954). In the Atiamuri area boulders of hydrothermally altered pumice breccia, similar to that at the Ohakuri Gorge, point to a source upstream from Ohakuri for the water which mobilized the lahar and deposited Smythe's Quarry Boulder Member.

Age

The age of the Atiamuri Beds is not known definitely. Stratigraphically the Atiamuri Beds overlie Whangapoa Beds of Pliocene or early Pleistocene age, and underlie the Hinuera Formation of Upper Pleistocene age, hence they are considered to be Pleistocene.

Hinuera Formation

Distribution and Content

The Hinuera Formation represents a period of aggradation of the Waikato River, in which large quantities of rhyolitic material were transported from the central volcanic regions. Henderson (1918) described the sediments above the Maungatautiri Gorge, and they have been recognized in various sections of the Waikato River downstream from Atiamuri (Mr J. Healy, pers. comm.).

At the dam site, coarse current bedded sands (Fig. 10) and fine gravels form the left bank 910 ft terrace 400 yards south-east of the

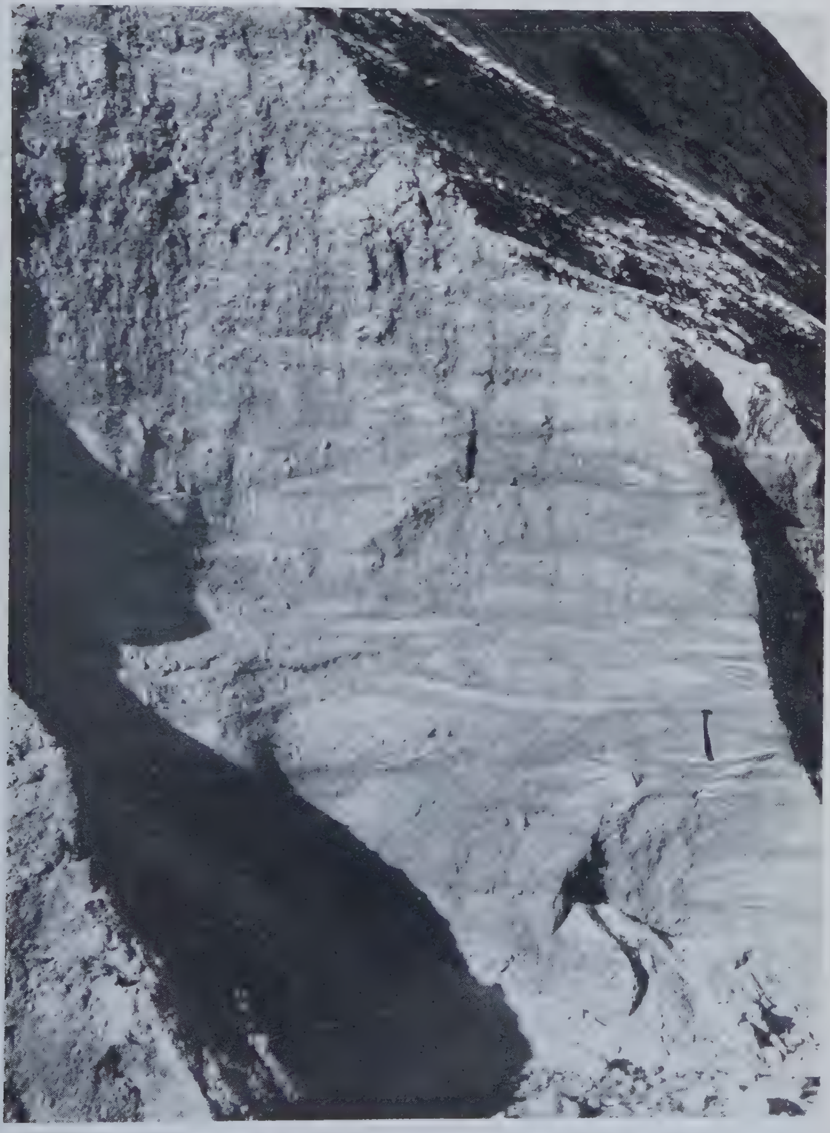

FIG. 10.—Hinuera Formation exposed in cutting in left bank 910 ft terrace beside Wairakei-Tirau State Highway. Photo shows typical current bedded sands near base of section and overlying gravels and sands.

proposed dam, and also a small area in the right bank between the river and the Whangapoa Beds on the southern slopes of Ngautuku.

The sands are loosely compacted and consist mainly of pumice, dark rhyolite, detrital volcanic glass, and feldspar crystals. They are separated by gravel beds up to 1 ft thick consisting of rounded rhyolite, hydrothermally altered and silicified pumice breccia, and pumice up to 6 in., and by an occasional thin bed of white pumice silt. Along the dam centre line on the left bank 910 ft terrace, hole 202 showed the Hinuera Formation to be 43 ft thick, and to consist of sands with a bed of rhyolite boulders 9 ft thick towards base. In the cliff face of the 910 ft terrace on the north side of the Tirau-Wairakei Main Highway (grid reference N85/501730) the section from the top is:

	Thickness		
R.L. 900 ft	8 ft	Volcanic ash	Recent Ash
	28 ft	Current bedded pumice and hydrothermally altered pumice breccia sands and small rhyolite pebbles with pumice lenses near the base.	Hinuera Formation
	20 ft	Gravels and current bedded sands and gravels. The gravels consist of hydrothermally altered pumice breccia up to 6 in. and pumice up to 2 in.	
	20 ft	Current bedded pumice sands and lenses of pumice up to 6 in. diameter with little or no fines.	
	27 ft	Alternating gravels and current bedded sands.	
R.L. 784 ft	13 ft	Coarse pumice sands	

Below this level talus obscures the section.

Thickness and Relation to Underlying Beds

On both banks the Hinuera Formation rests unconformably on the eroded surface of the Whangapoa Beds. As the base of the Hinuera Formation is at R.L. 756 ft in hole 38, and the top at 952 ft in hole 30, the original thickness probably exceeded 190 ft. The 910 ft terrace is not the aggradational surface of the Hinuera Formation, which filled the valley up to about 950 ft, but a degradational terrace.

Age and Correlation

The Hinuera Formation at Atiamuri is correlated on lithology with the Hinuera Formation of Upper Pleistocene age, described by Healy (1946) at Karapiro, where, as at Atiamuri, it is overlain by subaerial volcanic ash.

Recent Ash Members

Distribution and Content

Subaerial volcanic ash up to about 9 ft thick mantles the landscape above 780 ft around the dam site.

The following section measured in a cutting on the Tirau-Wairakei Main Highway (grid reference N85/506729) illustrates the sequence.

Thickness		Correlation
6 in.	Black soil containing pumice up to ¼ in.	
9 in.	Light brown fine pumice ash of sand-silt grade (i.e. less than 1/16 in.). Scattered fragments of rhyolite less than ¼ in.	
5 in.	Lighter brown pumice ash of sand grade with a silt matrix containing abundant pumice up to ½ in., mostly less than ⅛ in., with a silky texture when broken.	
8 in.	Medium grey pumice and rhyolite ash of sand grade, containing abundant pumice less than ¾ in., mostly about ⅛ in.; abundant black rhyolite mostly less than ⅛ in. Feldspar, clear glass, and acicular, brown-black hornblende less than 1/16 in., common. Charred wood at base.	Rhyolite Block Member?
1 ft 3 in.	Light brown, coarse pumice lapilli and charred wood in sand to silt grade matrix. Dense pumice up to 4 in., not common; vesicular pumice, mostly between 1 in. to 2 in., abundant. Sub-rounded rhyolite less than ⅛ in., fairly common. Clear glass less than 1/16 in. not very common; angular obsidian up to 1/16 in., and a black ferromagnesian mineral less than 1/32 in., fairly common. Charred wood, 2 in. in length, not common.	
1 in to 3 in.	Loose, coarse pumice lapilli consisting of abundant pumice mostly ½ in. but some up to 1 in., and fairly common rhyolite up to 1/16 in. In some sections pumice sands up to 1 in. thick separate two lapilli bands.	Taupo Lapilli Member
¼ in.	Steely grey, sand-silt grade ash.	Rotongaio Ash Member
¼ in.	Light grey pumice less than 1/16 in. in a silt grade matrix.	Hatepe Lapilli Member
1 ft 4 in.	Dark brown ash containing scattered pumice less than ¼ in.	Tirau Ash ?
4 ft 8 in.	Light brown ash containing scattered bleds of pumice silt up to 1 in. diameter.	
9 in.	Loose sand, containing weathered pumice up to 1 in. and grains of rhyolite, glass, and ferromagnesian minerals.	Hinuera Formation

Relation to Underlying Beds

The ash beds rest disconformably on the Hinuera Formation terrace top, and unconformably on the terrace face and on older formations. They appear to have been removed from the 830 ft left bank terrace.

Age and Correlation

The youngest dated subaerial ash layer, the Rhyolite Block Member, which conformably overlies the Taupo Lapilli Member (Baumgart, 1954; Baumgart & Healy, 1956) was dated by Fergusson and Rafter

(1953, N.Z. ^{14}C No. 1), and from correction required (Fergusson and Rafter, 1957) as 130 A.D. At Atiamuri correlation of ash deposits with the Taupo Rhyolite Block Member and the Tirau Ash is by no means certain, and further work remains to be done to determine thickness, distribution, and identity.

Taupo Terrace Alluvium

Distribution and Content

On the right bank of the river, fine pumice silts, sands, and gravels partly fill to a level of 860 ft, a valley cut in the Hinuera Formation and Atiamuri Pumice Breccia. On the left bank they partly fill an old channel at the foot of the 910 ft terrace. Horizontally bedded, fine pumice silts, sands, and gravels without ash cover, crop out in the face of the 860 ft terrace near the Bailey bridge, where the following section is exposed.

Thickness	
5 ft	Coarse, unbedded pumice sands and gravels up to 2 in. diameter.
50 ft	Bedded pumice sands and fine pumice silts with interbedded pumice pebble layers. Dip 2°.
9 ft	Massive pumice siltstone in three beds 3 ft thick.
20 ft	Unbedded pumice gravels up to 2 in. and fragments of charred wood.
3 ft	Tirau Ash Member.

Talus obscures the remainder of the section.

On the left bank near the 910 ft terrace the alluvium is bedded deltaically, the foreset beds dipping up to 25° south-east. Rounded to sub-angular, highly vesicular pumice up to 1 in. is predominant over angular, lithoidal rhyolite and fairly fresh, fine grained pumice breccia. The matrix consists of sand grade pumice, glass, feldspar, and ferromagnesian minerals. Charred wood is fairly common.

Thickness and Relation to Underlying Beds

In the dam area it is thickest (80 ft) in the terrace face north of the Bailey bridge, where it rests unconformably on the Tirau Ash Member.

Age and Correlation

These pumiceous sediments were deposited by the Waikato River during the latest Taupo eruptions of lapilli and pumice breccias. The basal pumice gravels containing fragments of charred wood are correlated with the Taupo Lapilli Member, which was erupted about 130 A.D. The fine silts and upper pumice gravels were probably derived partly by erosion of the Taupo Lapilli Member (e.g. left bank channel fill) and partly from later pumice breccias erupted in the Taupo area. Such eruptions, and a probable eruption of a coarse pumice breccia from which the upper coarse gravel was derived, are likely to be a little younger. Two carbon samples from the coarse breccia near the Bailey bridge are at present awaiting age determinations.

The Taupo Terrace Alluvium and the low-level river alluvium at grid reference N85 500740, and on the left bank downstream from the Bailey bridge, have been grouped together on the map as Recent Alluvium.

GEOLOGICAL HISTORY

Little is known of the pre-Pliocene history of the central North Island volcanic zone. By the end of the Tertiary this region, and other parts of New Zealand, were uplifted and dislocated by crustal movements. The main greywacke ranges were outlined by faulting and tilting, and in the central North Island basins were formed and partly filled with volcanic material (Grange, 1927). Faulting and the eruption of volcanic rocks has continued to the present day. In the Rotorua-Taupo area, the Pliocene was a period of eruption of numerous rhyolite domes of the Patetere Series. The buried rhyolite, the oldest rock encountered at Atiamuri, probably belongs to this period of volcanism. Later erosion removed most of the blocky scoriaceous rhyolite from the top of this dome. Fluviatile rhyolitic sandstones and siltstones (Dome Sandstone) were deposited on the rhyolite dome and then partly eroded, leaving remnants, some of which were encountered in the drill-holes.

The eruption of rhyolitic lavas of the Haparangi Series followed. Pumice breccias were then erupted, probably from nearby growing rhyolite domes. As the breccias are banded at the base through water sorting between eruptions it seems that a lake covering most of the Patetere Rhyolite dome may have been formed by the damming of a river downstream from Atiamuri either by lava flows or by faulting. If a lake was not present, then a fairly wide river must have flowed in the dam area, depositing sands and gravels. The breccias filled the lake and continued to build fans around the southern slopes of Ngautuku to a height of about 1,000 ft above sea-level.

A period of small scale normal faulting and hydrothermal alteration followed. The Patetere Rhyolite and the Whangapoa Beds were intensely silicified and hydrothermally altered near the dam site. Warm, silica-rich water altered and cemented the upper 60 ft to 110 ft of pumice breccia beneath the left bank 910 ft terrace, south as far as hole 24, but not as far as hole 30.

Following entrenchment of the Waikato River in the silicified pumice breccia (Whangapoa Beds), loosely compacted sands of volcanic origin were deposited and covered by subaqueous chalazoiditic tuffs, which were later eroded slightly a short time before the unstratified Chalazoiditic Pumice Breccia Member was erupted into the river valley.

The Atiamuri Granodiorite Boulder Bed, which rests on Whangapoa Beds, is believed to be younger than the Chalazoiditic Pumice Breccia Member, but the evidence is unsatisfactory.

The surface of the Chalazoiditic Pumice Breccia Member in the valley floor was eroded before the Chalazoidite Pebble and the Gravel Members were deposited. Later, a lahar, originating probably upstream from Ohakuri, partly filled the valley with blocks of pumice breccias and of siltstones similar to those beside the road near Rainbow Rapids, and of silicified and altered pumice breccia similar to that cropping out at Ohakuri. The lahar surface was eroded slightly before the river aggraded during Hinuera times, when a large quantity of newly erupted, fine volcanic detrital material carried down from the Taupo area to beyond Karapiro (Healy, 1946) overtopped the valley at Atiamuri, and spread laterally to a height of about 950 ft.

After the supply of volcanic material ceased, a period of erosion followed, and later volcanic ash (Tirau Ash—undated, to Taupo Lapilli Member) was spread over more than 8,800 sq. miles of the Central North Island (Grange, 1937). Wash from contemporaneous pumice showers, and subsequent pumice breccia eruptions in the Taupo area, choked the Waikato River and built a terrace (Taupo Terrace Alluvium) for most of its length below Taupo. Horizontally bedded pumice silts and sands above the volcanic ash on the right bank, and steeply dipping pumice sands and charred wood, suggest that a lake was formed in the Atiamuri area to a height of 860 ft. The river soon cut down again to the present level, with a halt at about 830 ft, during which some of the large boulders on the terrace were transported and concentrated as the finer matrix was removed.

ENGINEERING PROBLEMS

Dam Site

The Atiamuri hydro-electric station is to develop electric power from the Waikato River using the fall from about 835 ft, the proposed tailrace level of Ohakuri Station, to 753 ft.

The narrowest section of the valley is between 440 yards upstream and 220 yards downstream from the old highway bridge, and a natural site lies between the bridge and 220 yards downstream. The site chosen is 100 yards downstream from the bridge, and its development involves the construction of a concrete dam 150 yards across the top, a cut-off wall 300 yards long to the left bank 910 ft terrace, and a core wall into the terrace to prevent leakage.

The dam and powerhouse are to be founded on the buried summit of the rhyolite dome. The rhyolite is banded, and the flow bands, which dip at steep angles and strike (120° to 170°) downstream, define the direction of the major joints, which are from 1 ft to 3 ft apart.

Several joints were open and contained soft clay, which was removed during diversion race excavations. In the right bank powerhouse excavations, a zone of shattered flow breccia parallel to the flow bands extends downwards and will be excavated to a suitable depth. Apart from a thin cover of loose and very fractured rhyolite, which was removed from the diversion race area, little excavation was needed to expose fresh rock.

In the pumice breccias on the right bank, intersecting joints, and several normal faults, are filled with soft clay and hard silica. Although these faults show no sign of recent movement, the possibility of renewed movement should be considered.

Sands of the Rhyolitic Sand and Gravel Member exposed in the left bank cut-off wall would be unstable under load and would erode easily, and therefore should be either removed from any foundation area or compacted.

Rock Permeabilities

Ministry of Works staff measured water levels in drill-holes mainly on the dam centre line (Figs 1 and 2). On the left bank the water table is at about R.L. 753 ft from the river southwards for about 350 yards to the 910 ft terrace, where it rises to R.L. 807·5 ft with a gradient of 1 in 5. The high water table continues to hole 15, presumably because the breccia is not very permeable, and then falls to 754 ft in hole 24 (and 30), with a gradient of 1 in 11, in breccia of higher permeability. As the water table is below the proposed lake level (R.L. 823 ft) the possibility of leakage should be considered. West of the dam centre line, the few water levels available suggest a local rise in the water table. Farther downstream along the Mokai Road, the water table is expected to fall.

The diversion race on the left bank is below river level and 20 ft from the river. Grouting sealed the bulk of the rhyolite and the silicified breccias, but water entered through joints in the breccia below the base of the granodiorite boulder bed. This leakage was later sealed. The flow breccia on the right bank is severely shattered, soft and permeable, and would be difficult to grout effectively.

On the right bank the water table is flat and near river level to hole 22, approximately 370 yards north of the river. Although water levels were not measured in holes between holes 22 and 19, levels in holes 16, 18, and 19 indicate a rise towards Ngautuku. Part of the ridge near the old main highway bridge is silicified and readily grouted, but the hydrothermally altered pumice breccia would be difficult to grout. The poorly jointed unaltered pumice breccia towards Ngautuku would behave as a porous sandstone and would not grout easily.

The Hinuera Formation and Taupo Terrace Alluvium are highly permeable and would form serious leakage channels. They are unconsolidated also, and would erode easily at points where water emerges. Where they are likely to form serious leakage channels below the proposed lake level they have been removed.

Leakage Through Buried Channels

Each of the three major aggradations of the Waikato River, in which the Atiamuri Beds, Hinuera Formation, and Taupo Terrace Alluvium were deposited, produced changes in the river course. To locate buried channels, a line of holes was drilled across the valley and a magnetic survey, supplemented by seismic investigation, was used to guide drilling (Modriniak, 1951).

On the right bank, a saddle between hole 22 and Ngautuku suggested the presence of an old river channel. Outcrops of breccia on the north side of Whangapoa Road and information from drill-holes 16, 18, and 19 showed that no channel existed there.

A major buried channel at the foot of the left bank 910 ft terrace was outlined by a magnetic survey (Modriniak, 1951). In the cut-off wall the deepest section is steep sided and has a fairly flat bottom. It is 130 yards wide and extends down to a level of 709 ft in hole 373. To the north a lens of sands and gravels about 80 yards wide extends towards the river. It is overlain by the Chalazoiditic Pumice Breccia Member of the Atiamuri Beds, on top of which lie the three upper members of the Atiamuri Beds forming the 830 ft terrace. These leakage channels are being sealed by the left bank cut-off wall.

In hole 24, on the left bank 910 ft terrace, washings of sand-grade rhyolitic material, provisionally identified as cuttings from pumice breccia, were recovered from levels between 765 ft and 514 ft. If leakage in this area is likely to be serious, hole 24 should be redrilled and cores recovered to verify the presence of the Whangapoa Beds.

ACKNOWLEDGEMENTS

Thanks are expressed to Mr J. Healy, for the use of his detailed report (1949) and geological map prepared for Ministry of Works, and his helpful discussions of the geology. The geological map of the site before construction began (Fig. 1) is Mr Healy's map, to which only a few amendments were made, from additional outcrops exposed after felling of pine trees that had partly covered the area. Thanks are due also to Mr J. H. Mackay, Project Engineer, Mangakino, Mr R. E. Hermans, Engineer-in-Charge, Atiamuri, and their staffs, for helpful discussion and for supplying maps, plans, and information, and to Mr C. G. Vucetich (Soil Bureau, D.S.I.R.) for aid in identifying volcanic ash beds.

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RATIONALIZED FAULT INTERPRETATION

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Summary

The ratio of the horizontal and vertical components of displacement along a fault can be used to determine the character of the faults, and the direction of the Principal Horizontal Stress. The technique is applied to field examples.

A classification of faults, based on this ratio and the direction of the principal horizontal stress, is proposed and a new fault symbolism is suggested. The method is applied to fault-plane solutions proposed by Hodgson and tabulated by Scheidegger.

INTRODUCTION

Faults are controlled by stress in the earth's crust. Anderson (1942, p.12) defined types of faulting in relation to one of three possible stress components, namely the Principal Horizontal Stress (PHS).

Anderson's general proposition (*op. cit.*) that the PHS direction is normal to reverse faults and parallel to normal faults is the basis of the following discussion.

DISCUSSION

In general, no fault is simple in character. Typically, some lateral displacement accompanies normal and reverse faults, and conversely, some vertical displacement accompanies transcurrent faulting.

Along any particular fault the ratio of horizontal to vertical displacement (H/V) can be used to determine the direction of the PHS and the character of the fault.

By definition, for simple, normal, and reverse faults, the H/V ratio is zero, and for simple transcurrent faults this ratio is infinite. As the strike directions of normal and reverse faults intersect at right-angles, in any quadrant between the two the H/V ratio progresses from zero to infinity to zero. This relationship can be expressed by the equation

$$H/V = \tan 2\alpha, \qquad \text{..........} (1)$$

where α or its complement is the angle between the strike of the fault and the PHS direction (PHS angle).*

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*The equation $H/V = 2\alpha$ is a particular instance of $H/V = \tan x\,\alpha$, where x is chosen as an integer to take account of the fact that normal and reverse faults intersect at right-angles. Further, if x had a value other than 2, other types of faults with different properties should exist; so far none has been found.

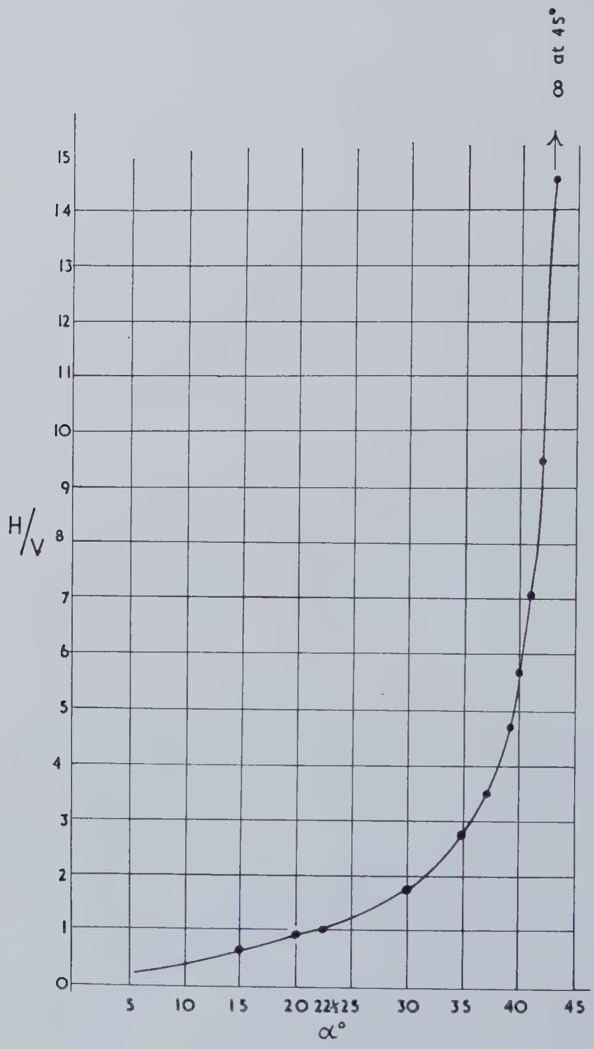

FIG. 1.—Relationship between H/V and α.

The value of α for a simple transcurrent fault, where $H/V = \infty$, is 45°. This angle corresponds to the angle between the PHS direction and Anderson's (1942, p. 14) plane of maximum tangential stress. Further, for $H/V = 1$, $\alpha = 22\frac{1}{2}°$ or $67\frac{1}{2}°$. Intermediate values for H/V and α are given in Fig. 1.

CLASSIFICATION OF FAULTS

The critical values of α for $H/V = 0, \pm 1$, and ∞ are plotted in Fig. 2 and a simple classification of faults according to their H/V value is suggested.

Four types of faults are recognized: normal (N), transcurrent clockwise (C), reverse (R), and transcurrent anti-clockwise (A), each occupying two opposite sectors of 45°. Within each sector the strikes of faults that are solely normal, reverse, or transcurrent, coincide with the bisectors of the sectors. Away from the bisector the character of the fault acquires increasingly a component typical of the faults that occur in the adjacent sector.

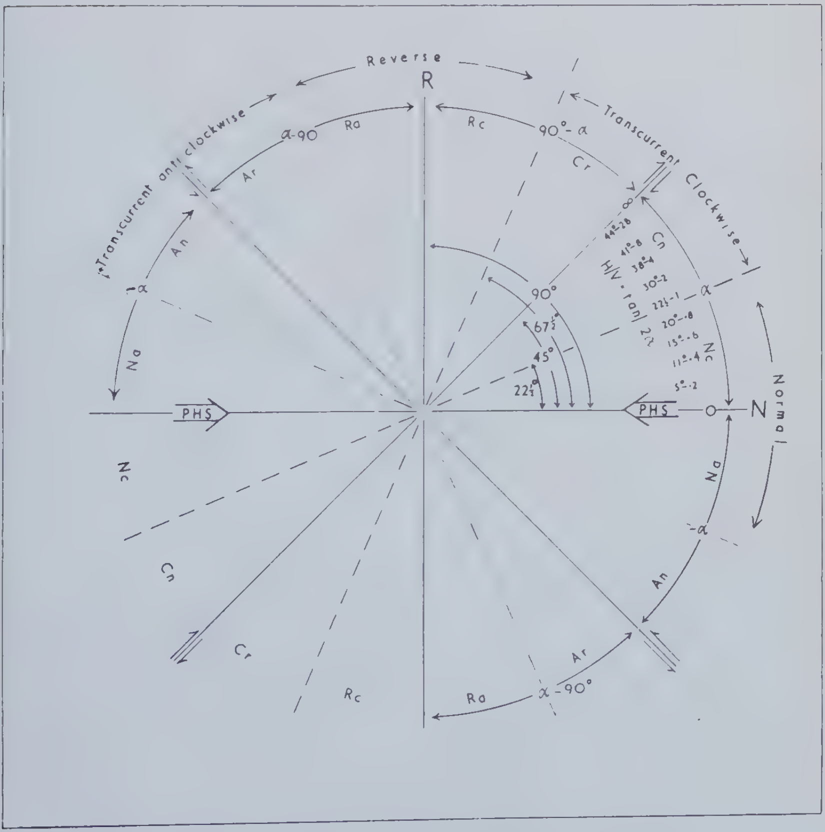

FIG. 2.—Relationship between PHS and faulting.

Tan 2α, and therefore H/V, become negative in alternate sectors, for example, in the sector of Rc and Cr (Fig. 2) tan 2α is negative, due to the reversal of the vertical displacement from normal to reverse sense. The reversal of the horizontal displacement occurs in the sectors Na and An, where the clockwise lateral component changes to an anti-clockwise component. This implies that for $\alpha = 0°, 45°$, and $-45°$ a reversal of one or the other component of displacement occurs.

Let us now consider the changes that occur in the nature of the fault with change in PHS angle. When the strike of a fault and the PHS direction are parallel, the fault is solely normal. As the PHS angle increases in anti-clockwise sense, the fault obtains a transcurrent clockwise component (Nc) till at 22½° the normal and the transcurrent clockwise components are equal. With a further increase in PHS angle the fault becomes purely transcurrent clockwise at 45° (C). With further increase in PHS angle the fault changes to a transcurrent clockwise fault with a reverse component. Continuing this process the following system results:

Symbol	Character of the fault	PHS angle
N	Normal	0°
Nc	Normal with transcurrent clockwise component	0° to 22½°
Cn	Clockwise transcurrent with normal component	22½° to 45°
C	Clockwise transcurrent	45°
Cr	Clockwise transcurrent with reverse component	45° to 67½°
Rc	Reverse with transcurrent clockwise component	67½° to 90°
R	Reverse	90°
Ra	Reverse with transcurrent anti-clockwise component	— (90° to 67½°)
Ar	Anti-clockwise transcurrent with reverse component	— (67½° to 45°)
A	Anti-clockwise transcurrent	— 45°
An	Anti-clockwise transcurrent with normal component	— (45° to 22½°)
Na	Normal with anti-clockwise transcurrent component	— (22½° to 0°)
N	Normal	0°

USE OF SLICKENSIDES

In the field it is often difficult to find reference surfaces or lines to measure the horizontal and vertical displacements along a fault. Once the direction of vertical displacement of a fault is known (reverse or normal), then the direction of pitch of slickensides will indicate whether the horizontal displacement along it is clockwise or anti-clockwise.

The following equation holds:

$$\cot \beta = H/V \qquad \text{.........} \quad (2)$$

where β is the pitch of the slickensides, Substituting (1) in (2)

$$\cot \beta = \tan 2\alpha \qquad \text{.........} \ (3)$$

From this equation the direction of the PHS and the true character of the fault can be determined.

The vertical character of the fault in Fig. 3 is normal. To cause the particular slickensides as illustrated, block S must also have moved in anti-clockwise sense. For the pitch of the slickensides of 15°, $H/V = 3{\cdot}7$ and $\alpha = 37°$. The PHS direction of the fault (An) is therefore the strike direction minus 37° (see Fig. 2). It should be noted that if the beds are not horizontal, the true vertical displacement on the fault must be calculated.

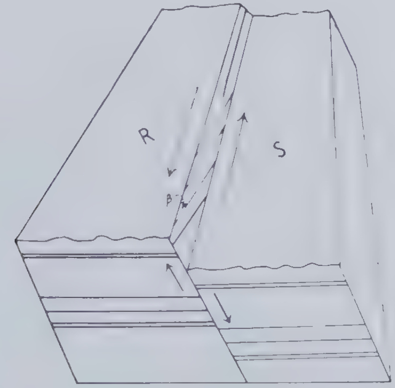

FIG. 3.—Slickensides as an indicator of α.

LIMITS OF APPLICATION

Although theoretically these methods are applicable to all faults, the character of minor faults, which generally extend downwards only a short distance, may be determined by local stress conditions, which deviate from the regional stress pattern (Moody and Hill, 1956).

MAP SYMBOLISM

The character of a fault may be indicated on a tectonic map in the following manner:

Consider a transcurrent clockwise fault striking at 030°, dipping north-west at 80° with the upthrown side to the NW. It is also known

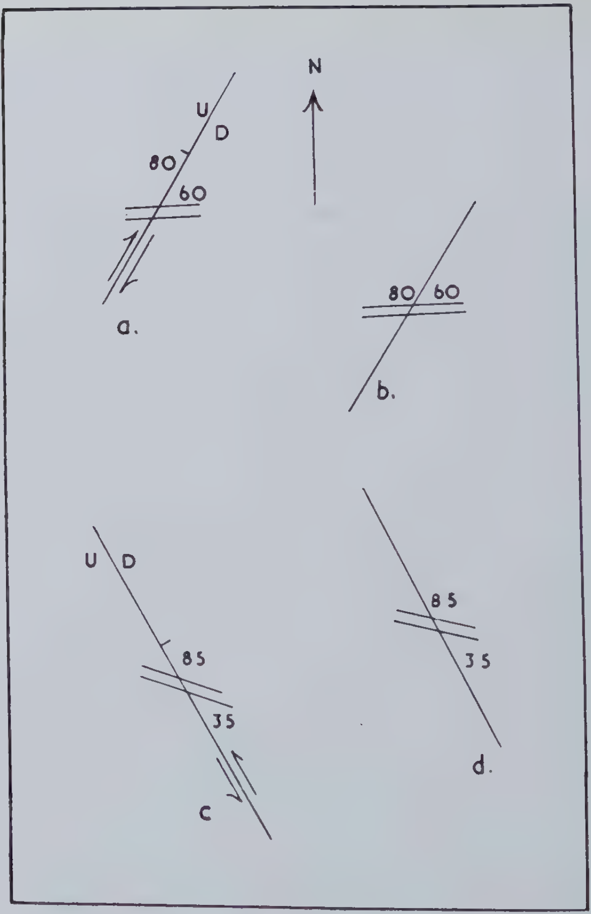

FIG. 4.—Conventional and proposed map symbolism.

that the PHS angle is 60°. The orthodox map symbolism is shown in Fig. 4a. The same data can be shown in a simpler form (Fig. 4b) if the following conventions are adopted:

(a) A double line, signifying the PHS direction across the fault;

(b) The value of the PHS angle (< 90°) on the downthrown side of the fault;

(c) The amount of dip in the supplement angle in the direction of dip.

Fig. 4c shows a transcurrent anti-clockwise fault striking at 340°, dipping NE at 85°, with the upthrown side to the SW. The PHS angle is — 35°. Fig. 4d shows the same data in the proposed symbolism.

EXAMPLES

(1) Two major faults in the same area can be expected to show the same direction of Principal Horizontal Stress. Data along the Awatere Fault and the Wairau Fault in the South Island of New Zealand (Wellman, 1953) are used to provide an illustration.

	Awatere Fault	Wairau Fault
Map sheet	NZMS 1, S53	NZMS 1, S27
Ref. No.	184	102
Strike E. of N.	055°	064°
H/V	170/5	33/3
α	45°	42°
Character	Cn	Cn
The PHS is thus given by the value of α + the strike	$45 + 055 = 100$	$42 + 064 = 106$
PHS direction	100° E. of N.	106° E. of N.

The difference in the PHS direction of 6° can be regarded as satisfactory, as this is within the accuracy of measurement.

(2) The same major fault with changing strike should also show the same stress direction. The Wellington Fault in the North Island of New Zealand, which was examined by the writer, was taken as an example.

	Wellington Fault	Wellington Fault
Map sheet	NZMS 1, N161	NZMS 1, N149
Strike E. of N.	058°	042°
H/V	60/15	40//10
α	38°	38°
Character	Cn	Cr
The PHS is thus given by the value of α + the strike	$38 + 058 = 096$	$(90 - 38) + 042 = 94$
PHS direction	096° E. of N.	094° E. of N.

This example also illustrates the change in character which accompanies a change in strike of the fault. This is obvious from consideration of Fig. 2.

(3) The PHS directions over a large region could be expected to show a consistent pattern. The uniformity in PHS directions, determined from data from Wellman (1955) and the author, is illustrated in Fig. 5, which takes in the northern part of the South Island and the southern part of the North Island. This demonstrates that in the area examined the application of the method reveals a consistent stress pattern.

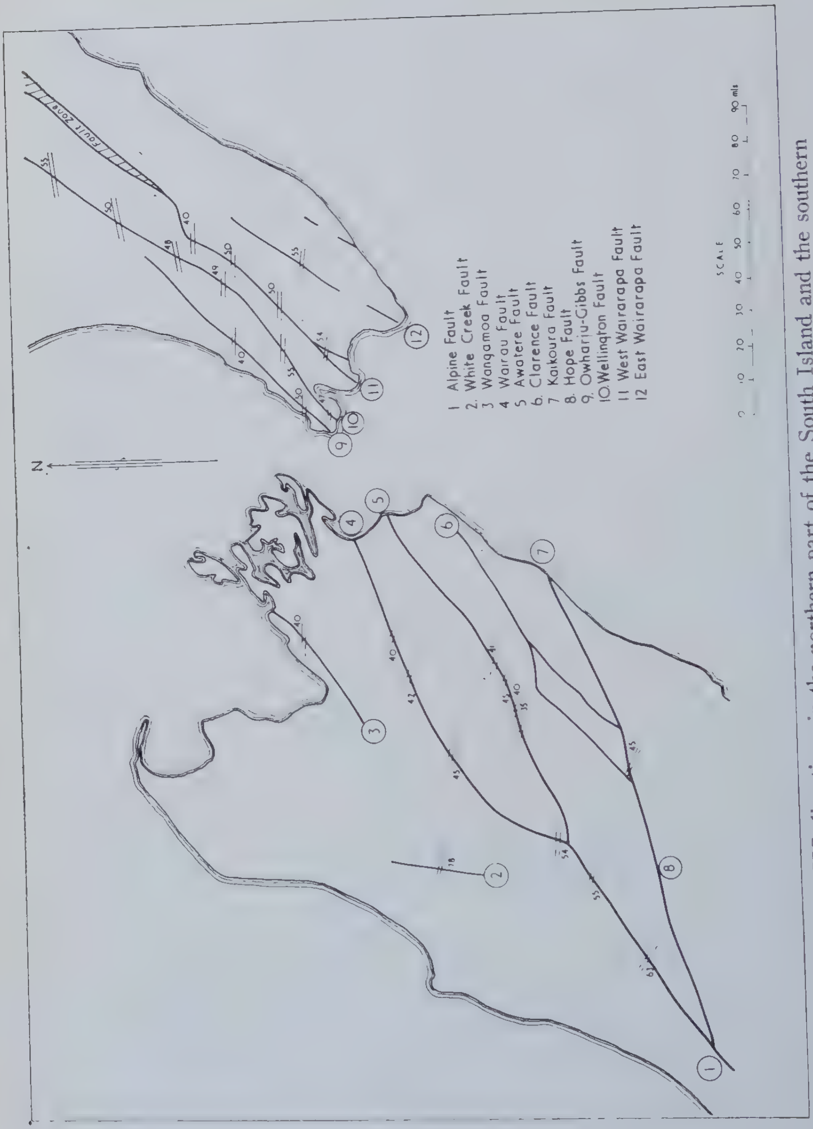

Fig. 5.—PHS directions in the northern part of the South Island and the southern part of the North Island of New Zealand.

(4) Slickensides are used in Fig. 6 where the strikes of the faults in the Buller area, in the South Island of New Zealand are plotted. The PHS directions were calculated as follows:

Fault	1	2
Strike E. of N.	040°	112°
Dip amount and direction	88° to NW	89° to SW
Upthrown side	SE	NE
Pitch slickensides	20° to 040° E	5° to 112° E.
Character	Cn	An
$\cot\beta = \tan 2\alpha$	2·75	11·4
α	35°	42°
PHS direction	40 + 35 = 075° E	112 — 42 = 070° E.

Again, this result is satisfactory. These PHS directions deviate from those illustrated in Fig. 5, as the fault pattern (Fig. 6) is Tertiary in age. The discrepancy between the PHS directions in the two diagrams supports the hypothesis, based on work in progress, that the Tertiary stress pattern differs from that of the present day.

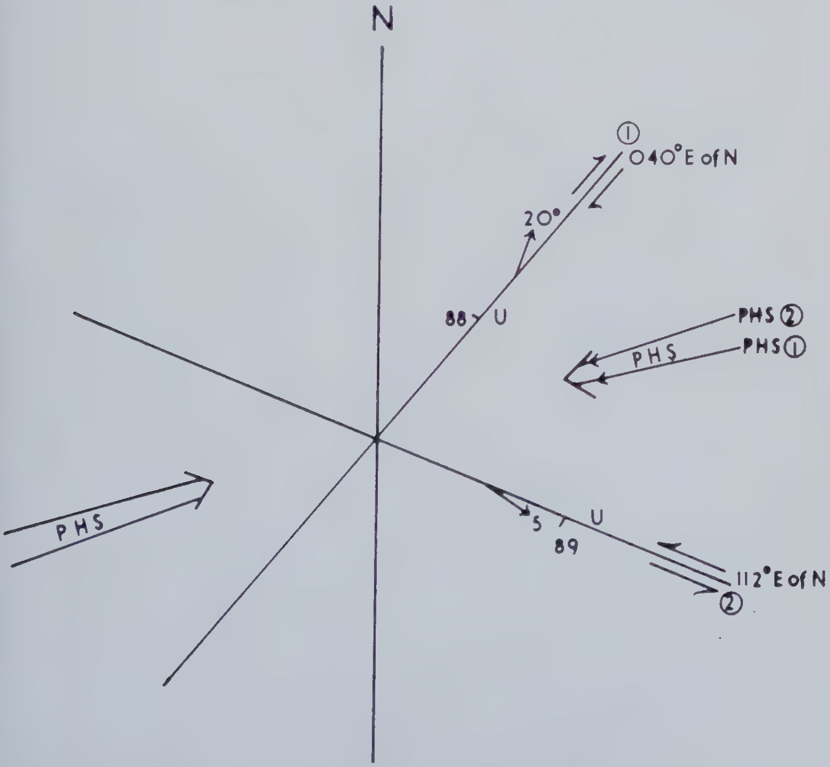

FIG. 6.—PHS directions derived from slickensides.

Application to Fault-Plane Studies

Hodgson (1955) and others used seismological data to determine the strike, dip, and character of faults that cause earthquakes. These authors arrived at two fault-plane solutions for each earthquake and gave the horizontal and vertical components of the displacements of the faults. From these data it is possible to establish PHS directions. From these directions it will be possible to plot a stress pattern covering regions where earthquakes occur. In Fig. 7 the PHS directions were determined from data from Hodgson and from Scheidegger. A PHS pattern emerges from PHS directions based on foci to a depth of 0·01 radius of the earth (R) which includes the thickness of the crust. PHS directions obtained from earthquakes below the solid crust (0·01 — 0·09 R) do not fit this crustal pattern. An insufficient number of earthquakes have yet been studied to give a reasonably complete stress pattern. As earthquakes with focal depths

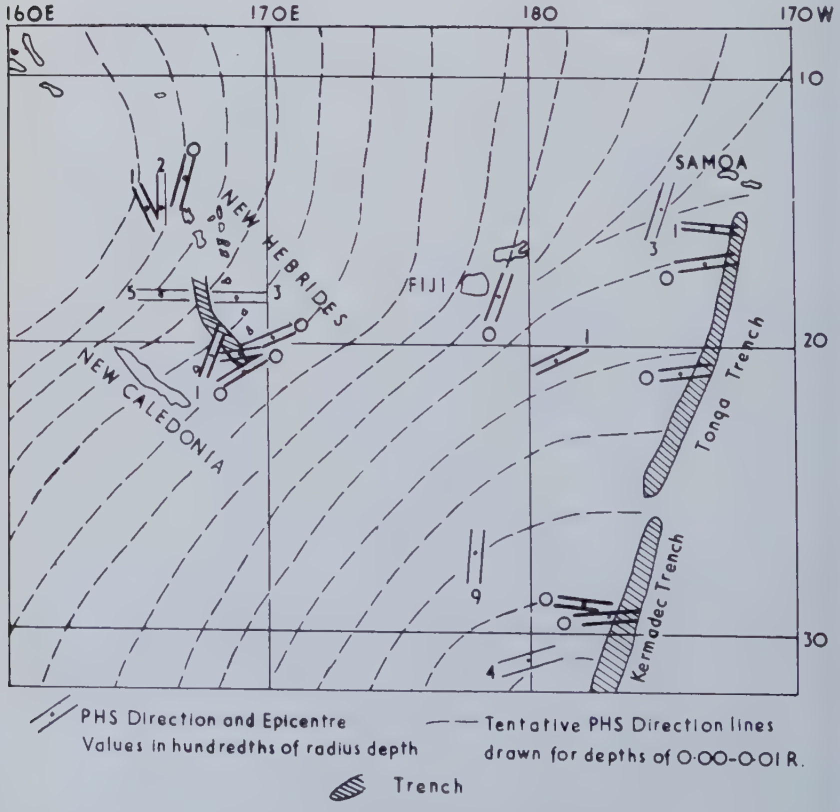
160E
170E
180
170W
10
20
30
SAMOA
NEW HEBRIDES
FIJI
NEW CALEDONIA
Tonga Trench
Kermadec Trench
2
1
5
3
1
3
1
1
9
4
PHS Direction and Epicentre
Values in hundredths of radius depth
Tentative PHS Direction lines drawn for depths of 0·00-0·01 R.
Trench

Fig. 7.—Stress pattern (tentative) for part of the South-West Pacific.

of more than 700 km have been recorded, it should ultimately be possible to draw stress patterns at selected horizons, thereby facilitating the study of sub-crustal stresses.

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A BOREHOLE SURVEY OF ILEMITE-BEARING BEACH SANDS AT CAPE FOULWIND, WESTPORT

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Summary

Posthole boring of dune sands on Nine Mile Beach, south of Cape Foulwind, Westport, shows that the surface sand to a depth of 20 ft contains an average of 5·5% of magnetically recoverable ilmenite.

Boring of dunes covering approximately half of Nine Mile Beach, has proved more than one million tons of ilmenite in sands above groundwater level. This represents only a small fraction of the total ilmenite present, above and below groundwater level, over the full extent of Nine Mile Beach.

INTRODUCTION

Previous work by Cox (1881), Hutton (1950), Nicholson and others (in press) has established the presence in beach sands of the West Coast, South Island, of appreciable quantities of ilmenite. Evaluation of the tonnages of ilmenite available and the percentage concentration of ilmenite in the sands was not carried beyond the stage of a preliminary reconnaissance survey, based on surface sampling and old dredging records. The purpose of the present investigation is to confirm by shallow drilling in one representative area, that ilmenite is present in the bulk of the sands and is not confined to small surface concentrates, to assess the magnetically recoverable percentage of ilmenite in the sand of that area, and to assess roughly the tonnage of ilmenite available above ground water level.

For this purpose, drill sampling was conducted on sand dunes between Tauranga Point and the Okari River. The area was chosen as representative of West Coast beach sand deposits, and because of its accessibility and proximity to Westport.

DRILLING METHODS

Drilling equipment consisted of a 3 in. hand-operated posthole borer with pipe extensions to permit boring to 30 ft depth. 20 ft proved to be the maximum depth attainable in sand, progress beyond that depth being extremely slow and unreliable owing to the scraping of

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sand from the walls of the hole during withdrawal and replacement of the drill rods and auger.

Drilling was stopped immediately if ground water was reached, progress below groundwater level being impossible owing to caving of the hole.

Material removed from the boreholes was carefully sampled on the spot by coning and quartering, a 20 lb sample being double-bagged whilst still damp, and transported to Wellington for further treatment.

Boreholes were sited as shown on the sketch map (Fig. 1), lines of holes being set out across the coastal dunes at 1-mile intervals. In addition, shallow (10 ft) holes, Nos 16, 17, 18, 19 were drilled at points intermediate between the above lines to give a fairly regular drilling pattern over the whole of the area, although no attempt was made at precise grid-boring.

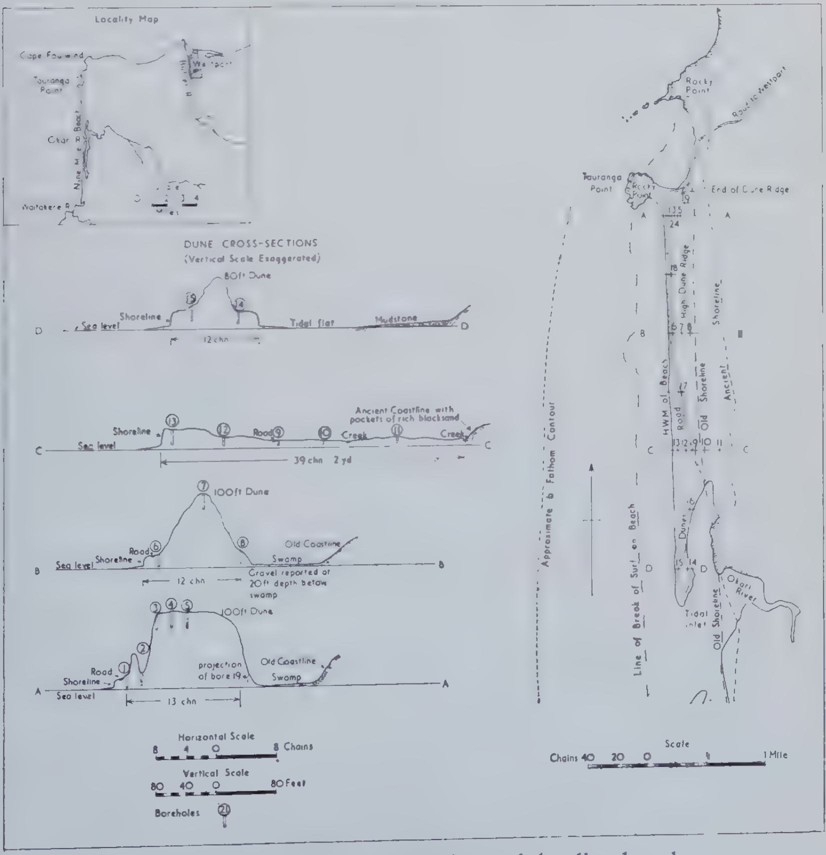

FIG. 1.—Plan and cross-sections of locality bored.

SAMPLING AND SEPARATION OF ILMENITE

The 20 lb samples were dry and free-running by the time they reached Wellington. They were therefore immediately reduced in size to about 1 lb by split trays after thorough mixing. The small samples were finally dried in an air oven at 150° C. 5·00-gram samples were then taken with great care to avoid segregation, which proved somewhat troublesome in the dried material, and any magnetite in the sample was removed by a hand magnet. The sample was then passed twice through a Frantz Isodynamic high-intensity magnetic separator to remove ilmenite. Both passes were made with the following setting:

Transverse slope	20°
Longitudinal slope	15°
Current	0·25 amp
Vibration	moderate
Feed rate	10 to 15 g/hr

The amount of ilmenite removed in the second pass did not exceed 5% of the amount removed in the first pass. Ilmenite removed was weighed to ± 1 mg, and the percentage in the sample calculated. The above procedure was considered to give results similar to those that would be attained by full-scale commercial high-intensity magnetic separation.

The ilmenite thus obtained from all samples was noted to be quite clean, containing very few grains of garnet, and one typical sample on analysis showed 43% TiO_2.

To determine the approximate percentage recovery of ilmenite by the above methods, heads, tails, and concentrates from one sample (hole 10) were analysed for TiO_2, recovery then being calculated as 65%. The writers consider that on a commercial scale this recovery could be improved by the use of more complex treatment methods, possibly involving grinding, electrostatic separation, or flotation.

The average amount of magnetically recoverable ilmenite in sands of the area was calculated at 5·5%.

QUANTITY ESTIMATES

For this approximate assessment of total tonnage of ilmenite above groundwater level in the area sampled, the cross-sectional areas of sand at each line of drill-holes were estimated as follows:

Widths of the dunes at each section were chained, cross-section sketches made on the spot, and heights of peaks determined from Department of Lands and Survey contour maps. The dunes were assumed to be composed entirely of sand, i.e. to contain no basement rocks above groundwater level, an assumption which the writers consider quite sound from geological evidence, and from reports on the history of the area (1947).

Average heights above groundwater level of the dunes at each cross-section were then estimated in a very conservative manner, allowing 10 ft as the average height of groundwater level above mean sea-level. From these average dune heights and from the chained widths the cross-sectional areas were calculated.

The cross-sectional areas were then averaged and the result multiplied by the total distance between drill-hole lines to estimate the total volume of sand. The total tonnage was then estimated using the value of 1·2 tons per cu. yard of sand, a conservative estimate for the material in question.

From the average of the percentages of ilmenite obtained from all boreholes, the total amount of ilmenite *above groundwater level* in this portion of the area was thus estimated at 1·36 million tons. Details of the quantity estimates are given in Table I.

It is realized that the above method of calculation is not highly accurate, and suitable only for preliminary estimates. It is, however, considered sufficiently accurate for present purposes, since the ore-body could not be completely delineated in depth, length, or width.

DISCUSSION

As indicated by the plan of Nine-Mile Beach, large quantities of sand are present south of the Okari River mouth. This sand was observed to be identical in appearance with that north of the Okari River, and is considered by Furkert (1947) to be of similar origin.

Geological evidence, and reports from prospectors in the area indicate that the sands should continue for depths of at least 30 ft below average groundwater level. In this connection, it is interesting to note that drill records of the Barrytown Gold Dredging Company Limited, operating in a similar beach deposit, show that black sands persist in that locality to depths of over 60 ft below groundwater level. The writers consider it highly probable that the material below water level will contain similar or higher percentages of ilmenite than the wind-blown dune sand sampled.

Isolated pockets of rich black sand containing 25 to 50% ilmenite were observed along the old coastlines indicated on the plan. These resources are not included in the above estimates.

Hence the present boring campaign has merely touched on the total ilmenite resources of the locality. An accurate estimate of the total amount and grade of ore in the locality would require drilling equipment capable of operating at least 100 ft below groundwater.

TABLE 1.—Calculations for Quantity of Magnetically Recoverable Ilmenite.

BOREHOLE DATA

Bore number	Depth (ft)	Depth to groundwater (ft)	Magnetically recoverable ilmenite (%)	Location of bore	Remarks
1	18·5	—	2·8	Edge of road, 0.2 mile S. of fork in road	
2	17	17	3·6	2 ch. E. of bore 1	Rich at 4 ft, rich at ground-water level
3	19·5	—	3·1	2 ch. E. of bore 2	2 ft of sandy soil at surface
4	20	—	1·7	2 ch. E. of bore 3	2 ft of surface soil, soil band at 12 ft
5	20	—	2·0	2 ch. E. of bore 4	
6	20	—	5·9	At edge of road, 1 mile S. of bore 1	1 ch. from high-water mark
7	20	—	4·1	6 ch. E. of bore 6	
8	18	18	4·5	5 ch. E. of bore 7	
9	5	5	11·0	Edge of road, 1 mile S. of bore 6	
10	4	4	9·7	6 ch. E. of bore 9	1 ft of surface soil
11	8	8	1·7	10 ch. E. of bore 10	2 ft of surface soil
12	10	10	9·5	6 ch. W. of bore 9	4 ft of rich surface sand
13	20·5	—	9·6	6 ch. W. of bore 12	
14	17	17	5·1	3 ch. from E. edge of spit, 1 mile S. of hole 9	
15	20	—	9·5	6 ch. W. of bore 14	
16	10	10	9·3	2 ch. from E. edge of spit, 0·5 mile N. of bore 14	
17	10	—	3·8	Edge of road, 0·5 mile N. of bore 9	
18	10	—	4·3	Edge of road, 0·5 mile N. of bore 6	
19	10	—	3·2	Leeward edge of dune ridge, ch. S. of road	
AVERAGE	15		5·5		

VOLUME DATA

Sketch map cross-section	Estimated average depth to groundwater level	Width	Estimated cross-section area
	(ft)	(yd)	(sq. yd)
A–A	70	286	6670
B–B	40	264	3520
C–C	10	860	2870
D–D	30	264	2640
		AVERAGE	3920
Distance between section A–A and D–D			5280 yd
Estimated volume of sand		5280 × 3920	20·7 × 10^6 cu. yd
Estimated tonnage @ 1·2 t./cu. yd		20·7 × 10^6 × 1·2	24·8 × 10^6 t.
Estimated tonnage of magnetically recoverable ilmenite		24·8 × 10^6 × ·055	1·36 × 10^6 t.

CONCLUSIONS

(1) The sampling carried out confirms the presence of ilmenite in the bulk of the dune sand between the Okari River mouth and Tauranga Point.

(2) More than one million tons of magnetically recoverable ilmenite is available above groundwater level in sand dunes between the Okari River mouth and Tauranga Point. The dune sand contains an average of 5·5% of magnetically recoverable ilmenite, the content varying between 1·7% and 11%. Approximately 30% of the total tonnage of ilmenite estimated is present in sand averaging 8% ilmenite, the remainder averaging 4% ilmenite.

(3) It is obvious that the total amount of ilmenite available, above and below groundwater level, over the full extent of Nine-Mile Beach, is many times greater than the 1·36 million tons proved by the above borehole survey.

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PETROGENETIC IMPLICATIONS OF THE 1954 NGAURUHOE LAVA AND ITS XENOLITHS

By A. Steiner, New Zealand Geological Survey, Department of Scientific and Industrial Research

(Received for publication, 12 March 1958)

Summary

The Ngauruhoe lava erupted in 1954 is an olivine-bearing basaltic andesite, and belongs to the Taupo volcanic association of basalts, basaltic andesites, pyroxene andesites, dacites, rhyolites, and ignimbrites. This association, as indicated by a variation diagram, is divided into three distinct series: (a) a main basic series, displaying continuous variation from basalts to dacites; (b) a continuous acid series of rhyolites and ignimbrites; and (c) an accumulative series of basalts and basaltic andesites.

A characteristic feature of the 1954 Ngauruhoe lava is the abundance of small quartzose and feldspathic xenoliths, and intensely vitrified gneissic xenoliths of boulder size. Structural, petrographic, and chemical data indicate that all the xenoliths are derived from acid gneiss. Limited miscibility between acid syntectic melt and basic host magma is shown by gradational contact of the vitrified xenoliths.

Petrochemical study of the effusive rocks of the Taupo volcanic association indicates that, with the exception of the accumulative series, the sum of the alkaluminous oxides remains constant during magmatic differentiation. This constancy is one of the characteristics distinguishing the Taupo volcanic association from the Hawaiian basalt-trachyte association.

The parent magma of the main basic series has been derived from olivine basalt magma by selective assimilation of acid gneiss. Limited fractional crystallization of this contaminated magma, controlled by the constancy of the sum of the alkaluminous oxides, produced the lavas of the basalt-dacite range, the dacites being the last differentiates. The rhyolites and ignimbrites are excluded from being derived by fractional crystallization of the contaminated basaltic magma. The accumulative basic lavas have formed from the uncontaminated olivine-basalt magma by gravitational crystal accumulation and limited fractional crystallization.

The similarity in chemical composition between the vitrified xenoliths and the rhyolites and ignimbrites suggests that the acid effusive rocks of the Taupo volcanic association originated from an acid magma produced by transfusion of acid gneiss in prolonged contact with olivine basalt magma at great depth. Within the acid series fractional crystallization is also restricted by the constancy of the sum of the alkaluminous oxides.

INTRODUCTION

This paper presents the results of petrological study of the xenoliths and their basic host lava erupted from Ngauruhoe during the year 1954. This study has led to important petrochemical and petrogenetic implications.

The eruption of Ngauruhoe in 1954 has been fully described by Gregg (1956). Ngauruhoe is situated in the Taupo volcanic zone (Fig.

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1) which stretches from the Ruapehu to the White Island volcano (Hochstetter, 1864). For the basalts, basaltic andesites, pyroxene andesites, dacites, rhyolites, and ignimbrites, occurring in this volcanic zone, the name Taupo volcanic association is proposed. Their age ranges

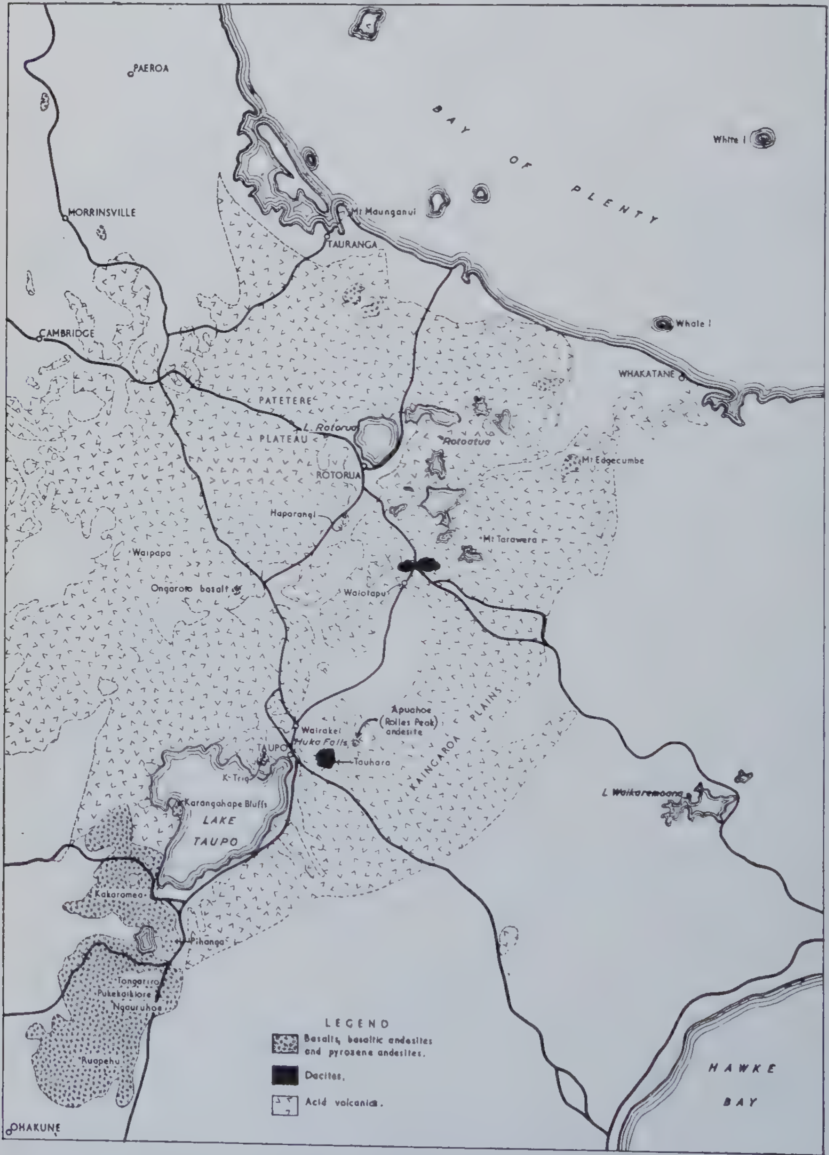

FIG. 1.—Map showing distribution of effusive rocks in the Taupo volcanic zone.

from Pliocene to Recent times. Most of these volcanics have been described by Grange (1937). No outcrops of plutonic rocks are known in the Taupo volcanic zone.

A characteristic feature of the 1954 Ngauruhoe lava is an abundance of xenoliths (Gregg, 1956), with those of gneissic origin predominating. Xenoliths in earlier lavas erupted from Ngauruhoe and Ruapehu have been reported by Speight (1908), Grange and Williamson (1930), Battey (1949), and Cloud (1951).

This study has been concerned with three major problems arising from the presence of xenoliths:

(a) the nature of the country rocks underlying the volcano, particularly of the rocks below the greywacke basement;

(b) evidence of interaction between xenoliths and host magma;

(c) effect of such interaction on the petrogenetic relationship within the basalt-andesite range, a relationship which Tilly (1951) regards as one of the most important problems of volcanic petrogenesis.

LAVA

Petrography

The fourteen lava specimens (*P 13843, 13844, 14588, 14589, 16944-8, 16951-3, 16955, 16958) examined from various flows possess similar megascopic and microscopic properties. They contain the same minerals in approximately the same proportions. All are dark grey to black, more or less vesicular, finely porphyritic rocks in which common phenocrysts of plagioclase and hypersthene, and rare olivine and augite, are embedded in a glassy groundmass that makes up 50% of the volume of the rock (Fig. 2). The diameter of the vesicles is less than 0·7 mm. The groundmass is in places semi-opaque and irresolvable, being crowded with minute granules of magnetite. Usually, however, it consists of dark brown transparent glass containing acicular pyroxene microlites less than 6μ long and 0·9μ wide. Less commonly, the glass contains plagioclase microlites, producing a hyalopilitic texture.

The phenocrysts average 35 to 40% of the volume of the rock, the ratio of hypersthene to plagioclase being 1:2. The plagioclase phenocrysts, not more than 1·5 mm. across, display oscillatory zoning, the zones being thin and numerous. However, it should be noted that the cores of some feldspar crystals are slightly less basic than the adjacent mantle. This reverse zoning suggests, that the cores of these crystals represent relics of xenolithic feldspar that has not been completely assimilated

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*Numbers refer to rocks and thin sections in collections of the New Zealand Geological Survey.

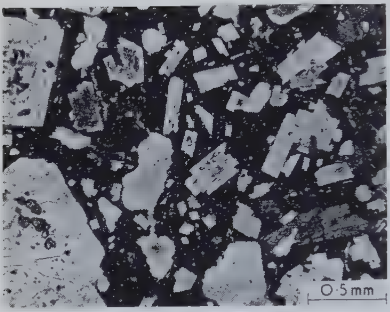


FIG. 2.

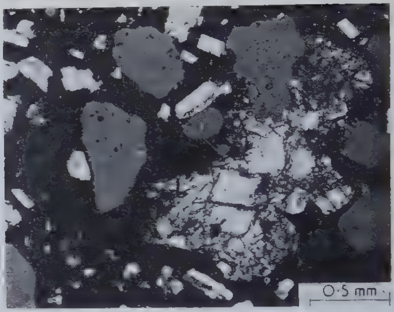


FIG. 3.

FIG. 2.—Photomicrograph of the 1954 Ngauruhoe lava showing phenocrysts of plagioclase and hypersthene in glassy, vesicular groundmass (P 16869). Ordinary light, × 40. *Photo, A. L. Tilbury.*

FIG. 3.—Photomicrograph of olivine phenocrysts surrounded by a group of hypersthene crystals in the 1954 Ngauruhoe lava (P 13844). Polarized light, × 40. *Photo, A. L. Tilbury.*

by the magma. Many glassy inclusions in the centre, and/or arranged in two to four zones, can be noted in some plagioclase phenocrysts. Less common is plagioclase containing blebs of augite and hypersthene; these blebs are also zonally arranged, hypersthene being external to augite. The plagioclase varies over a wide range from basic labradorite (An 65) to bytownite (An 77). This composition is inferred from measured indices of refraction according to data given by Winchell (1951).

Hypersthene occurs either in single subhedral crystals, not exceeding 1·0 mm. in length, or, less commonly, in glomeroporphyritic groups. The composition of hypersthene is En 60 as inferred from its measured refractive index $\gamma = 1{\cdot}715 \pm 0{\cdot}002$ according to the values listed by Winchell (1951).

Olivine, where present, is almost always surrounded by a group of hypersthene crystals (Fig. 3). Augite, on the other hand, occurs in single crystals displaying lamellar twinning. Because augite and olivine are rare, no attempt has been made to determine their composition from optical data.

It should be stressed that xenoliths are a common constituent of the Ngauruhoe lava of 1954. The lava erupted from Ngaruhoe in 1949 is also rich in xenoliths as noted by Battey (1949). The xenoliths found in the 1954 lava are described in detail in a later section.

Chemical Composition

The result of chemical analysis of a representative sample of the 1954 lava is given in Table 1 (No. 6). This analysis has to be used with caution because of the contamination of the analysed sample with minute quartzose and feldspathic xenoliths, the removal of which was not practicable. The sample is estimated to contain not more than 0·1% of quartzose xenoliths and not more than 5% by volume of feldspathic xenoliths. These figures represent the amounts of both types of xenoliths observed generally in the 1954 lava (D. R. Gregg, pers. comm.).

The analysis of the contaminated rock is closer to that of Nockolds' average andesite than to his average "Central" basalt (Nockolds, 1954). However, the presence of 9·1% normative quartz (Table 2) is incompatible with modal olivine and basic plagioclase. Perhaps this normative value indicates approximately the amount of silica of xenolithic origin.

The chemical analysis does not appear to be a suitable criterion for classifying the lava. The basic nature of the plagioclase (An 65 to An 77) and the presence of olivine indicate a basalt. On the other hand, the abundance of hypersthene suggests a pyroxene andesite. The most appropriate classification appears to be an olivine-bearing basaltic andesite.

GNEISSIC XENOLITHS

Petrography

Three types of gneissic xenoliths occur in the 1954 lava:

quartzose xenoliths, small, with sharp contact and usually showing incipient transfusion, are relics of quartzose bands of quartzo-feldspathic gneiss;

feldspathic xenoliths, also small, with sharp but irregular contact, showing at present no sign of transfusion, represent re-melted, modified, and re-crystallized feldspathic bands of quartzo-feldspathic gneiss.

Intensely vitrified xenoliths of boulder size, quartzo-feldspathic in composition, commonly show relict gneissic structure, and transitional contact with the enclosing lava.

Quartzose Xenoliths: The most conspicuous are the snow-white, angular to rounded, sugary quartzose xenoliths. These consist largely of clear quartz with average grain size of 0·2 mm., and with mosaic and sutured textures. Small amounts of granular and subhedral diopside and rare magnetite are usually intermixed with the quartz. Some large xenoliths contain an abundance of fibrous and prismatic wollastonite (Fig. 4). Quartzose xenoliths of similar mineral composition occur in the 1949 Ngauruhoe lava flow (Battey, 1949).

The quartzose xenoliths usually display incipient transfusion into colourless glass, particularly along the intergranular boundaries. Minute apophyses of this glass extend into the centre of some quartz grains. The new melt also attacks diopside and wollastonite. The refractive

TABLE 1.—Chemical analyses of forty-five effusive rocks of the Taupo volcanic association (Nos. 1 to 45), three xenoliths of vitrified acid gneiss (Nos. 46 to 48), and one xenolith of poryphyritic microdiorite (No. 49) from the 1954 Ngauruhoe lava, granitic boulder found by drilling at Huka Falls (No. 50), and of Nockold's average andesite (No. 51) and "Central" basalt (No. 52).

	1	2	3	4	5	6	7	8	9
SiO_2	49·52	51·16	51·46	53·70	54·91	55·90	55·73	56·63	57·24
TiO_2	1·15	0·80	0·81	0·71	0·48	0·76	0·59	0·81	0·81
Al_2O_3	17·32	17·12	17·07	15·10	12·73	16·90	13·25	16·71	16·75
Fe_2O_3	3·81	2·40	2·05	2·50	1·02	2·10	2·08	1·16	1·54
FeO	7·03	7·25	6·82	6·65	6·41	6·30	5·13	7·00	6·44
MnO	0·19	0·18	0·18	0·16	0·17	0·15	0·14	0·16	0·12
MgO	6·01	6·12	6·04	7·60	11·29	5·20	8·88	4·85	4·58
CaO	11·41	11·41	11·43	10·50	8·34	8·40	9·91	8·16	7·95
Na_2O	2·50	2·28	2·40	2·40	1·88	2·60	2·32	2·85	2·74
K_2O	0·33	0·54	0·64	0·60	0·67	1·00	0·76	1·61	1·49
H_2O+	0·25	0·27	0·56	0·20	1·02	tr.	0·43	0·21	0·20
H_2O-	0·26	0·15	0·17	0·08	0·72	0·06	0·30	0·10	0·02
P_2O_5	0·19	0·13	0·10	0·12	0·10	0·10	0·13	0·16	0·17
BaO	0·01	0·05	0·07	0·005	0·02		0·03	0·03	0·025
SrO	0·01	0·02	0·01	0·02	0·02		0·01	0·01	0·01
ZrO_2		none	none						nt.fd.

	10	11	12	13	14	15	16	17	18
SiO_2	56·22	56·90	56·44	57·80	57·70	58·57	59·64	60·09	60·16
TiO_2	0·70	0·52	0·71	0·59	0·73	0·72	0·71	0·70	0·70
Al_2O_3	17·41	14·50	14·44	14·10	16·81	16·45	16·09	16·42	16·35
Fe_2O_3	8·60	2·55	1·09	1·60	1·40	1·67	0·88	1·69	1·23
FeO		5·40	5·78	5·95	5·71	5·34	5·54	4·58	4·89
MnO	—	0·13	0·16	0·14	0·16	0·17	0·17	0·10	0·10
MgO	4·17	7·20	8·35	6·90	4·30	4·67	4·67	4·03	4·03
CaO	7·15	8·90	7·17	9·40	7·68	7·22	7·05	6·82	6·82
Na_2O	2·25	2·45	2·72	2·40	2·90	3·04	3·00	3·40	3·37
K_2O	1·66	0·60	1·39	0·80	1·14	1·50	1·47	1·83	1·81
H_2O+	1·84	0·55	0·94	0·15	0·69	0·24	0·36	0·07	0·16
H_2O-		0·24	0·51	0·08	0·41	0·13	0·14	0·06	0·05
P_2O_5	nt.dt.	0·08	0·15	0·10	0·16	0·15	0·15	0·24	0·24
BaO		0·005	0·03	0·01	0·03	0·04	0·04	0·03	0·035
SrO		0·02	tr.	0·05	tr.	tr.	tr.	0·07	0·06
ZrO_2			none			none	none	nt.fd.	nt.fd.

	19	20	21	22	23	24	25	26	27
SiO_2	62·57	62·16	62·50	67·2	67·23	71·55	68·48	72·57	72·41
TiO_2	0·69	0·71	0·79	0·55	0·34	0·40	0·29	0·30	0·30
Al_2O_3	16·19	14·32	14·45	15·9	15·12	14·37	14·14	14·04	13·91
Fe_2O_3	2·75	1·64	2·20	2·65	3·33	1·61	2·39	1·63	1·53
FeO	3·19	4·33	3·81	1·5	0·50	1·27	0·72	0·86	0·86
MnO	0·12	0·15	0·09	0·10	0·09	0·07	0·05	0·10	0·08
MgO	2·68	3·97	3·69	1·2	2·02	0·71	0·25	0·48	0·19
CaO	6·14	5·89	5·51	3·5	4·25	2·86	2·28	2·25	1·73
Na_2O	3·02	2·49	2·84	3·6	3·55	4·12	3·42	3·69	4·51
K_2O	1·77	2·37	2·43	2·4	2·20	2·79	3·23	3·41	3·23
H_2O+	0·59	1·21	0·70	0·55	0·68	0·28	2·53	0·27	0·34
H_2O-	0·24	0·29	0·77	0·75	0·49	0·21	1·64	0·24	0·46
P_2O_5	0·14	0·12	0·15	0·18	0·11	0·11	0·03	0·09	0·08
BaO	0·04	0·10	0·07		0·06	0·09	0·07	0·06	0·08
SrO	0·01	none	0·01				nt.given		
ZrO_2		none							

TABLE 1.—*Continued.*

	28	29	30	31	32	33	34	35	36
SiO_2	73·26	72·15	72·86	71·91	71·56	72·09	73·43	74·29	72·81
TiO_2	0·31	0·29	0·26	0·29	0·30	0·25	0·30	0·25	0·31
Al_2O_3	13·74	14·30	13·58	13·76	12·97	13·27	13·53	13·56	12·83
Fe_2O_3	1·45	1·72	1·30	0·69	0·85	1·63	1·12	0·92	0·47
FeO	0·90	0·65	0·91	1·32	1·27	0·76	1·01	0·62	1·31
MnO	0·07	0·09	0·09	0·07	0·08	0·07	0·07	0·03	0·06
MgO	0·50	0·24	0·53	0·53	0·50	0·32	0·43	0·35	0·39
CaO	1·85	1·34	1·95	2·14	1·61	1·46	1·68	1·71	1·58
Na_2O	3·80	4·24	3·53	3·96	3·34	3·54	3·45	3·54	3·46
K_2O	3·73	2·94	3·71	2·78	3·92	3·50	3·38	4·12	4·09
H_2O+	0·27	1·18	0·23	1·83	3·11	2·76	0·76	0·18	2·50
H_2O-	0·23	0·44	0·60	0·47	0·20	0·47	0·49	0·38	0·08
P_2O_5	0·04	0·09	0·09	0·03	0·09	0·03	0·03	0·08	0·07
BaO	0·08	0·11	0·07	0·12	0·07	0·07	0·08	0·08	0·08
SrO	nt.fd.	—		0·01		—	trace		
ZrO_2		0·01		0·03		trace	0·02		

	37	38	39	40	41	42	43	44	45
SiO_2	74·37	74·53	71·75	75·08	74·74	75·55	75·76	76·52	75·39
TiO_2	0·22	0·22	0·26	0·26	0·20	0·21	0·19	0·12	0·14
Al_2O_3	13·46	13·06	12·62	13·05	13·10	12·78	12·87	12·48	12·89
Fe_2O_3	1·13	0·50	0·74	0·61	1·31	0·34	0·29	1·13	1·24
FeO	0·76	1·25	1·04	0·72	0·35	1·07	0·89	0·30	0·26
MnO	0·04	0·07	0·07	0·04	0·05	0·05	0·07	0·02	0·03
MgO	0·39	0·38	0·40	0·36	0·11	0·22	0·16	0·13	0·16
CaO	1·96	1·52	1·55	1·44	1·26	1·45	1·29	1·03	0·91
Na_2O	3·86	3·56	3·11	3·69	4·47	3·98	4·38	3·52	2·94
K_2O	3·18	4·23	4·07	4·27	3·20	3·64	3·11	3·88	3·69
H_2O+	0·25	0·27	3·33	0·14	0·53	0·35	0·46	0·52	1·24
H_2O-	0·18	0·04	0·62	0·13	0·29	0·04	0·12	0·33	0·90
P_2O_5	0·04	0·09	0·09	0·07	0·02	0·02	0·03	0·07	0·07
BaO	0·08	0·08	0·09	0·09	0·14	0·13	0·13	0·08	0·095
SrO				—	—	—	trace	nt.fd.	trace?
ZrO_2				nt.fd.	0·04	0·04	0·02	0·01	trace

	46	47	48	49	50	51	52
SiO_2	73·99	74·80	74·50	60·2	72·20	54·20	51·33
TiO_2	0·20	0·19	0·18	0·27	0·21	1·31	1·10
Al_2O_3	14·00	15·20	14·90	18·4	13·90	17·17	18·04
Fe_2O_3	0·25	0·10	0·30	0·6	0·95	3·48	3·40
FeO	2·85	1·75	1·55	6·3	1·95	5·49	5·70
MnO	0·03	0·11	nt.given	0·13	0·06	0·15	0·16
MgO	1·50	0·75	0·65	2·3	0·75	4·36	6·01
CaO	0·60	3·30	2·35	7·7	2·70	7·92	10·07
Na_2O	3·00	1·50	1·40	3·3	4·00	3·67	2·76
K_2O	2·80	1·70	2·10	0·5	2·80	1·11	0·82
H_2O+	0·05	0·05	0·15	0·15	0·20	0·86	0·45
H_2O-	0·10	0·03	0·05	0·15	0·05	—	—
P_2O_5	0·09	0·07	nt.given	0·12	0·08	0·28	0·16
BaO				—			
SrO							
ZrO_2							

TABLE 2.—Normative Composition of the Ngauruhoe Lava of 1954.

Normative minerals	
Q	9·1
or	6·0
ab	23·5
an	32·0
di	7·2
hy	18·4
mt	2·3
il	1·2
ap	0·3
	100·0

index of the intergranular glass is $n = 1{\cdot}484 \pm$ indicating an acid composition (George, 1924) but distinct from that of the silica glass formed by simple fusion of quartz.

There is no noticeable evidence of interaction between the host magma and its quartzose xenoliths. In fact, the sharp contact between xenoliths and lava, and absence of a reaction rim are characteristic features of the quartzose xenoliths occurring in the 1954 lava. It should be noted, however, that pyroxene rims around quartzose xenoliths enclosed in basic lavas elsewhere have been reported by several workers and reviewed by Holgate (1954).

Feldspathic Xenoliths: Dark grey feldspathic xenoliths are more abundant than the quartzose xenoliths but are much less conspicuous because their colour almost matches that of the lava. They are elongated,

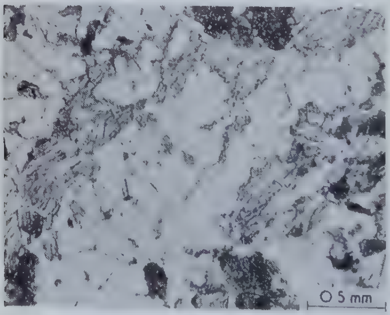


FIG. 4.

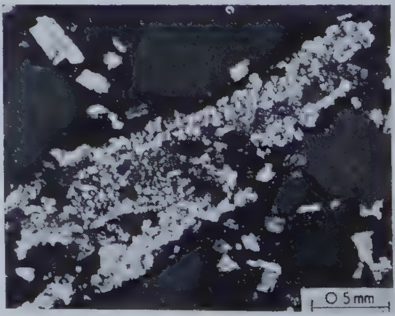


FIG. 5.

FIG. 4.—Photomicrograph of quartzose xenolith with wollastonite (P 16866). Ordinary light, × 40. *Photo, A. L. Tilbury.*

FIG. 5.—Photomicrograph of feldspathic xenolith surrounded by glassy, vesicular groundmass (P 13844). Polarized light, × 40. *Photo, A. L. Tilbury.*

angular to round and generally vary from 2 mm. to 20 mm. Two to four feldspathic xenoliths are seen in each thin section of the lava (Fig. 5).

The finely grained feldspathic xenoliths are made up predominantly of equigranular plagioclase and a few intensely corroded crystals of hypersthene (Fig. 6). Granular magnetite is a rather rare constituent. The dark brown mesostasis of the host lava tends to penetrate into the xenoliths, making the sharp contact between the lava and the xenolith rather irregular. Trails of the mesostasis often extend deep into the xenolith, enveloping many feldspar crystals with a thin film of glass.

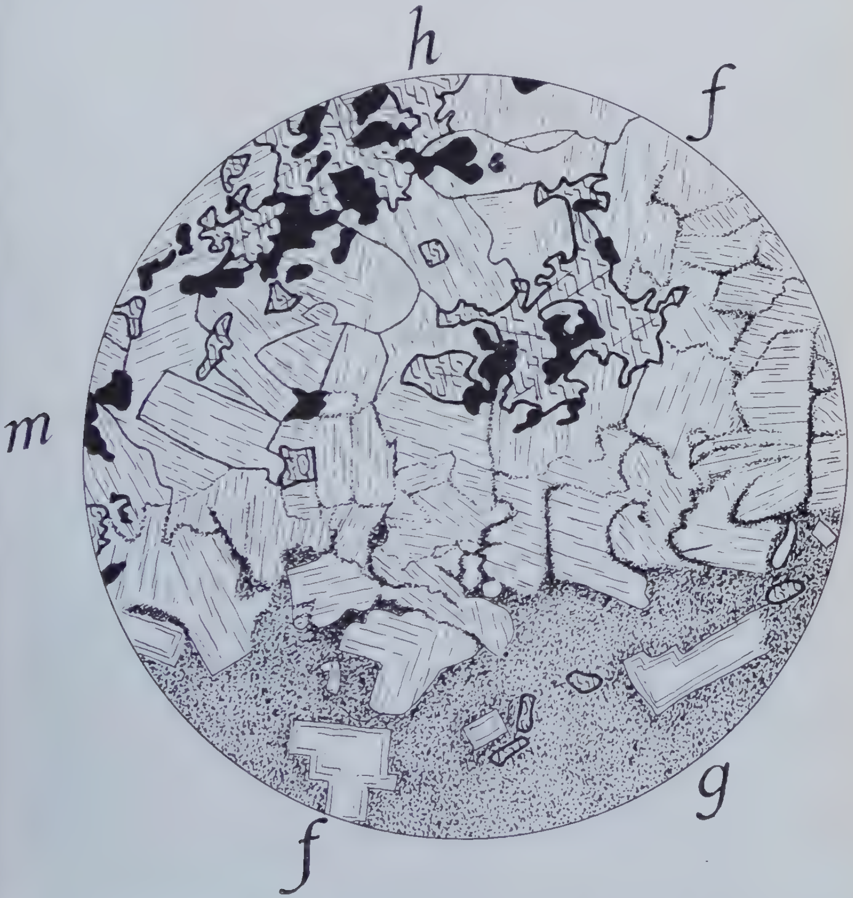


FIG. 6.—Camera lucida drawing showing basaltic glass intruding from the surrounding lava into the feldspathic xenolith (P 16869). Ordinary light, × 300.

f = feldspar
g = glass
h = hypersthene
m = magnetite

Drawing, R. C. Brazier.

The plagioclase crystals, in average not more than 0·035 mm. across, show albite twinning but no zoning. Their composition, An 65, corresponding to a labradorite, has been inferred from measured indices of refraction according to data given by Winchell (1951).

In some instances a few somewhat larger and intensely zoned plagioclase crystals occur along the contact with the lava. Occasionally, hypersthene protrudes from the lava partly into the xenolith (P 13844), and the portion of this hypersthene lying within the xenolith is always strongly corroded. This hypersthene and the zoned plagioclase occurring along the contact originate from the host lava. It seems that the material making up the xenolith was liquid at the time when hypersthene in the magma was already crystallized, and that the hypersthene was not in equilibrium with the liquid which on crystallization gave rise to the feldspathic xenolith. Evidently, the feldspathic xenoliths were in a molten state at some stage of the cooling history of the host magma.

From the textural relationship between the feldspar making up the xenolith and the glassy mesostasis penetrating into the xenolith from the host lava, it would appear that the xenolith was crystallized before

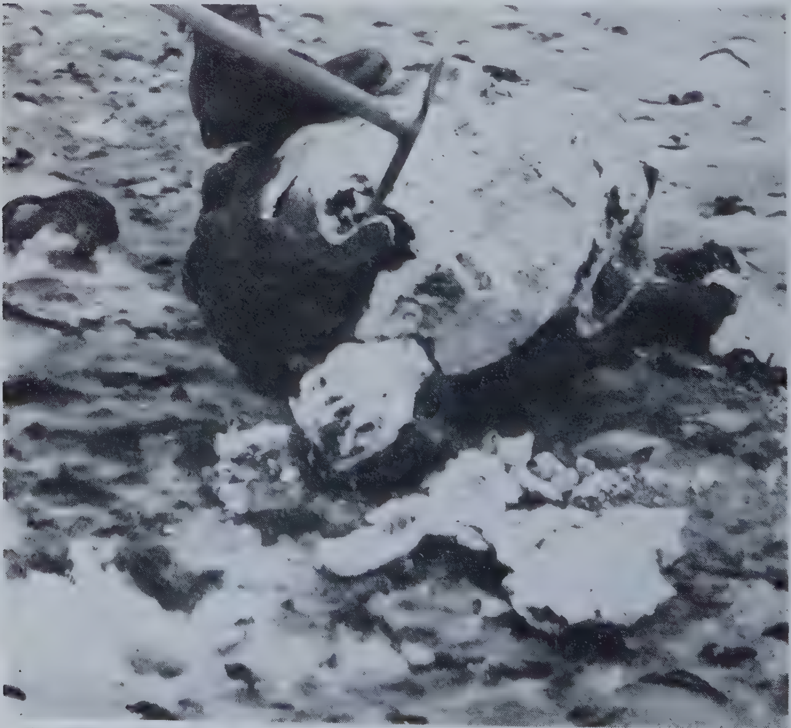


FIG. 7.—Vitrified xenolith of boulder size found in the moving face of the flow (18/8/54) and removed for sampling purposes (P 13847).

Photo, E. F. Lloyd.

the solidification of the host magma was completed. The residual liquid of the crystallizing magma was seemingly still highly fluid and, therefore, able to penetrate into the fine interstices between the plagioclase crystals.

Feldspathic inclusions made up largely of plagioclase also occur in the Ngauruhoe lava of 1949 (Battey, 1949).

Intensely Vitrified Xenoliths: Abundant greatly vitrified xenoliths of boulder size, up to 3 ft across, have been observed by Messrs D. R. Gregg and E. F. Lloyd, Rotorua (pers. comm.) in the lava flow of 18/8/54, and in the glowing avalanche of 16/9/54. According to them, such xenoliths are less common in earlier flows of the 1954 eruption. Fig. 7 shows an intensely vitrified xenolith (P 13847) found in the

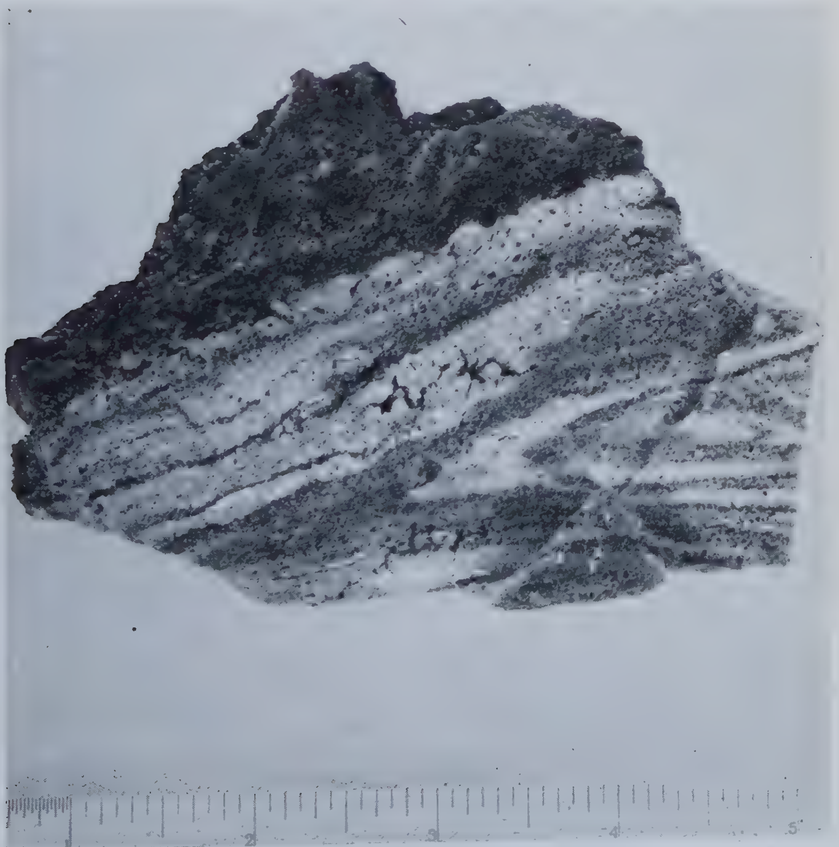


FIG. 8.—Hand specimen cut from vitrified xenolith of boulder size, showing relict banded and lensoid structure characteristic of gneiss (P 16867).
Photo, S. N. Beatus.

moving face of the flow (18/8/54), and removed for sampling purposes. Hand specimens cut from two similar xenolithic boulders (P 16867 and P 16868) are shown in Figs 8 and 9 respectively.

The highly vitrified and inflated xenolith P 16867 displays megascopically a relict banded and lensoid structure characteristic of gneiss (Fig. 8). Alternating dark and pale bands, concordantly arranged, contrast strongly in colour, their width varying from 1 to 5 mm.

The xenolith P 16868 (Fig. 9) has the appearance of grey pumice with intercalated dark to black lamellae alternating with white thin bands and trains of white streaks. Both the dark lamellae, 1 to 4 mm. in width, and the white bands, commonly 0·5 to 1·5 mm. wide, show conspicuous parallel alignment. A few white larger patches of somewhat irregular shape, and up to 4 cm in length, however, are located across the direction of alignment.

Under the microscope it can be seen that the xenoliths P 16867 and 16868 are essentially made up of colourless glass with numerous rounded vesicles. The refractive index of the glass of the xenolith P 16867 is $n = 1{\cdot}488 \pm 0{\cdot}001$, the corresponding value of P 16868 ranging from 1·489 to 1·494. These values should be compared with the refractive index of the glass of the rhyolitic rocks occurring in the Taupo volcanic zone; the latter averages $1{\cdot}500 \pm 0{\cdot}002$.

The vesicular nature of the xenolithic glass testifies that the glass has been liquid at some stage of the cooling history of the host lava. The vesiculation precludes the possibility of the glass being formed in the solid state as was suggested by Holmes (1937) for tranfused quartzite zenoliths in alkaline basic lavas elsewhere.

The glass encloses abundant highly corroded relics. Quartzose relics, consisting of minute single grains and mosaics of various size, predominate in the pale bands seen in Fig. 8. Similarly, the white parallel aligned streaks and the white patches lying across the direction of alignment in Fig. 9 consist essentially of finely grained quartzose mosaics. In addition, they contain varying amounts of fibrous or massive wollastonite and small amounts of twinned idioblastic oligoclase and clear glass. An iron oxide mineral is an accessory. The refractive indices of the wollastonite are $\alpha = 1{\cdot}620 \pm 0{\cdot}002$, and $\gamma = 1{\cdot}633 \pm 0{\cdot}002$. Tuhs, the birefringence 0·013 indicates that the mineral is not pseudowollastonite.

Small rounded or rectangular spongy aggregates (Fig. 10) and comparatively large, elongated relics (Fig. 11) consisting essentially of a thermally decomposed prismatic mineral are characteristic of the dark bands in Fig. 8. These larger relics also contain a small amount of a granular iron oxide mineral which is aligned in parallel trains and partly replaced by pyrite. The contrasting mineral composition of the alternating pale and dark bands seems to be a characteristic feature.

The evidence suggests that the spongy aggregates have been derived by a more progressive decomposition of the prismatic mineral making

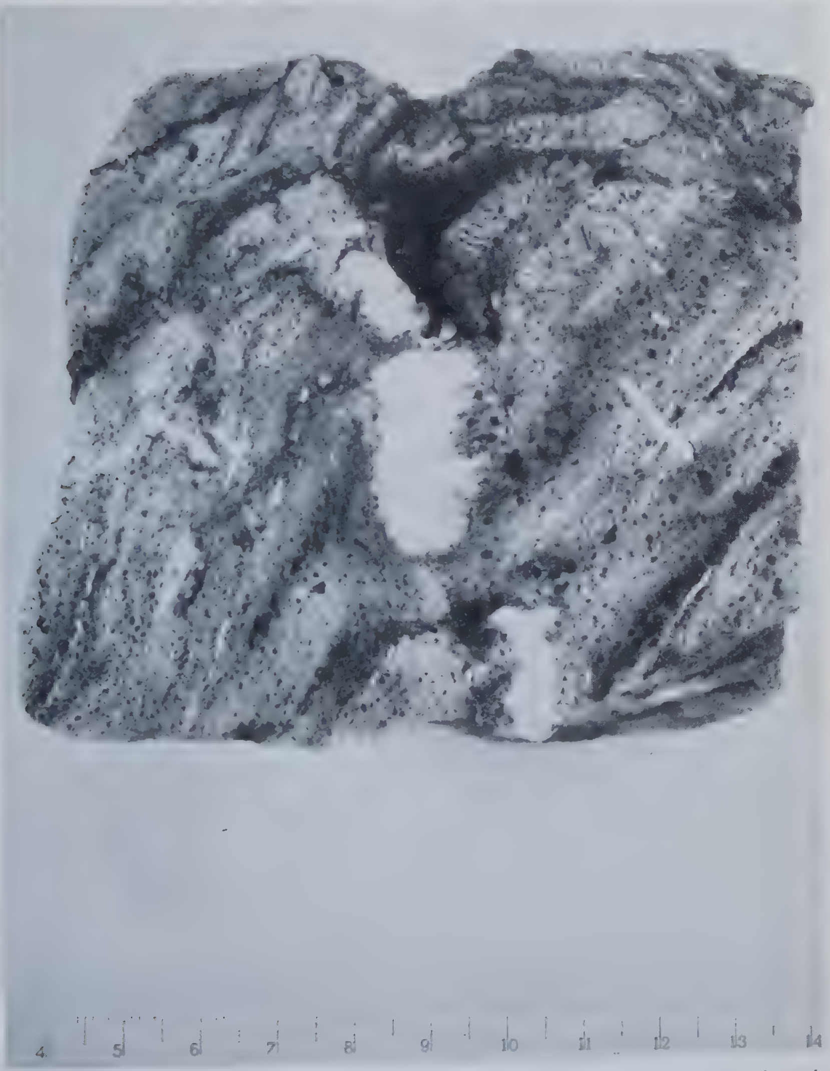


FIG. 9.—Hand specimen cut from vitrified xenolith of boulder size, having the appearance of pumice with intercalated dark grey to black lamellae alternating with white streaks and bands (P 16868). *Photo, S. N. Beatus.*

up the larger relics. Optical identification of the spongy aggregates and the prismatic mineral is rendered impossible because of their greatly advanced decomposition, but both have some resemblance to fritted feldspar. Nevertheless, the prismatic mineral exhibits negative elongation and a conspicuous parallelism indicating lineation, as shown in

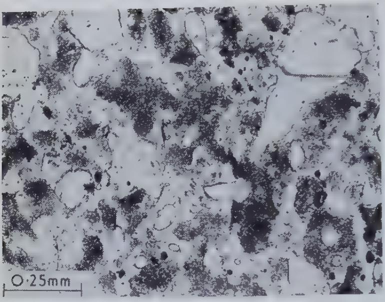


FIG. 10.

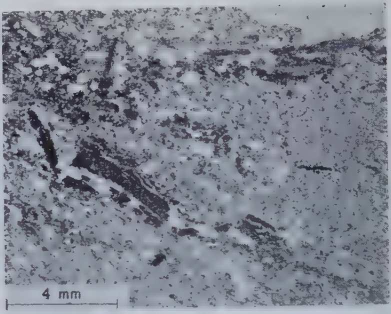


FIG. 11.

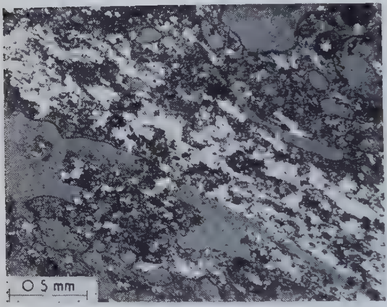


FIG. 12.

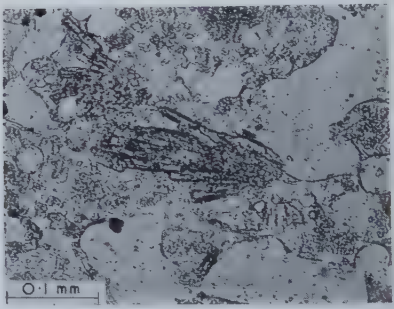


FIG. 13.

FIG. 10.—Photomicrograph showing spongy aggregates enclosed by colourless, vesicular glass in vitrified gneissic xenolith (P 16867). Ordinary light, × 80. *Photo, A. L. Tilbury.*

FIG. 11.—Photomicrograph of large elongated relics characteristic of dark bands of gneissic xenolith (P 16867). Ordinary light, × 7. *Photo, A. L. Tilbury.*

FIG. 12.—Photomicrograph showing lineation of thermally decomposed prismatic mineral making up the dark bands in gneissic xenolith (P 16867). Polarized light, × 40. *Photo, A. L. Tilbury.*

FIG. 13.—Photomicrograph of thermally decomposed sheaf-like aggregates in extremely vitrified gneissic xenolith (P 16869). Ordinary light, × 225. *Photo, A. L. Tilbury.*

Fig. 12. This lineation, together with the relict banded and lensoid structure and the bands of contrasted mineral composition. is considered to be conclusive evidence of the xenoliths originating from a quartzo-feldspathic gneiss.

It should be noted that some extremely vitrified xenoliths show no relict structure or texture (P 16869 and P 16870). It appears that extreme vitrification has entirely destroyed the last traces of the original structure and texture. These xenoliths consist predominantly of glass containing numerous finely grained aggregates of a spongy decomposition product, a notable amount of quartzose mosaics, and a few relics of plagioclase. Pyrite is an accessory. The spongy aggregates comparable with the spongy decomposition product of the xenoliths with gneissic structure occasionally enclose a relic of greatly corroded plagioclase. This textural relationship suggests that the spongy aggregates are a thermal decomposition product of plagioclase. The feldspar occurring in the xenolith P 16869 has the composition An 15, this being inferred from measured refractive indices (Winchell, 1951).

A prismatic mineral intensely decomposed is an additional minor constituent of the xenolith P 16869. It occurs in sheaf-like aggregates (Fig. 13) or in single prismatic crystals in average 0·11 mm long and 0·018 mm wide. Under crossed nicols this mineral appears greatly decomposed, though it has more or less retained its shape. The thermal decomposition renders its optical identification impracticable.

Relics of plagioclase and its decomposition product and quartzose mosaics provide the only clues to the original petrographic character of the extremely vitrified xenoliths. These constituents indicate a rock essentially of quartzo-feldspathic composition. It should be also noted that the refractive index of the glass making up the structureless xenoliths P 16869 and P 16870 ($n = 1 \cdot 488 \pm 0 \cdot 001$ and $1 \cdot 490 \pm 0 \cdot 001$, respectively) is almost the same as that of the xenoliths with gneissic scructure. From this evidence it is concluded, therefore, that the structureless, extremely vitrified xenoliths have also been derived from a quartzo-feldspathic gneiss.

It is noteworthy that muscovite usually associated with quartzo-feldspathic gneisses, has not been observed; nor have its common decomposition products. The hydroxyl-bearing muscovite, being near the lower end of the reaction series, would be more susceptible to reactive solution than feldspar and quartz. As the vitrification of the gneissic xenoliths is highly advanced, it appears that the muscovite has been already incorporated without trace in the syntectic melt.

Further, it should be pointed out that the vitrified xenoliths show a transitional contact revealed by a gradational glassy zone developed between the lava and the xenoliths. This zone is irregular, dark brownish grey to black and occasionally highly lustreous; its width does not exceed 5 mm. Although in hand specimen the contrast sometimes appears to be sharp, under the microscope, a gradational zone is commonly visible (Fig. 14). The glass of the transitional zone is generally light brown but becomes progressively darker towards the enclosing lava, and grades in the opposite direction, into the colourless glass making up the xenolith.

The average refractive index of the transitional glass of the xenolith P 16867 is $n = 1 \cdot 500 \pm 0 \cdot 002$, the corresponding value of the xenolith P 16870 ranging from 1·508 to 1·512. Actually, the refractive index of the transitional glass grades progressively from $1 \cdot 490 \pm 0 \cdot 001$ to $1 \cdot 541 \pm$, these limiting values being the refractive indices of the colourless xenolithic glass (P 16870) and the glassy mesostasis of the host lava, respectively.

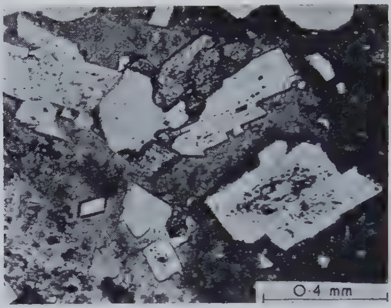


Fig. 14.—Photomicrograph showing transitional contact between vitrified gneissic xenolith and host lava (P 16869). Ordinary light, × 78.
Photo, A. L. Tilbury.

Phenocrysts of the lava, and spongy decomposition products and quartz mosaics of the xenolith are scattered throughout the glass of the transitional zone, and intermingling of the basic and acid glass is noticeable all along the contact. Patches of dark glassy mesostasis surrounding a phenocryst of hypersthene or plagioclase can be seen enclosed in the xenolith near its contact with the lava. These patches, undoubtedly detached from the host lava, merge gradually into the surrounding colourless, acid glass.

Chemical Composition

Results of chemical analyses of three vitrified gneissic xenoliths, P 13849, P 16867, and P 16869 given in Table 1 (Nos 46 to 48), show that the extremely vitrified but structureless xenoliths (Nos 47 and 48) are similar in composition to the xenolith with gneissic structure (No. 46) and that all three xenoliths are of acid composition. Thus, the xenoliths are derived from an acid gneiss, this being in agreement with their quartzo-feldspathic character.

Because the vitrification of the xenoliths P 13847, P 16867, and P 16869 is greatly advanced, the composition of the glass is expected to approach that of the whole xenolith. The values for the refractive index of the xenolithic glass indicate that the glass of these three xenoliths contains approximately 75% SiO_2. The silica content, as shown by the chemical analyses, ranges from 73·9% to 74·8%. Thus, the chemical and petrographic results are in close agreement.

Origin

The origin of the quartzose and feldspathic xenoliths is not obvious, and a hypothesis is advanced assuming fragments of quartzo-feldspathic gneiss being engulfed by basic magma. Undoubtedly, their temperature increases, and this causes at first an unequal expansion of bands of contrasted mineral composition. Later, an appreciable increase in volume takes place due to partial vitrification of non-quartzose bands which transfuse more readily than quartz. The combined dilatation utimately leads to a complete loss of coherence and mechanical breaking up of gneissic xenoliths preferably along the planes of foliation. The quartzose bands thus become completely separated from the remaining non-quartzose material, broken up, and dispersed into the host magma. These quartzose fragments, scattered throughout the magma, are presently found in the congealed lava as quartzose xenoliths which are actually remnants of gneissic fragments. Battey (1949) suggested that the quartzose xenoliths occurring in the 1949 Ngauruhoe lava, perhaps represent thermally altered Tertiary sandy limestone.

Heat would obviously affect small gneissic xenoliths more intensely than large xenoliths of boulder size. This explains why only large gneissic xenoliths have been preserved in their entirety, though they are intensely vitrified. Consequently, the quartzite xenoliths are derived from genissic fragments of considerably smaller size than that of the vitrified boulders.

It should be stressed that the quartzose xenoliths are petrographically comparable with the quartzose relics occurring in vitrified gneissic boulders. However, the quartzose fragments scattered throughout the magma remain almost unaffected by the basic magmatic liquid, which evidently has a slight corrosive power on quartz. The refractory nature of quartzose xenoliths immersed in basic magma elsewhere has been earlier observed by various workers (Holgate, 1954). Acid syntectic melt, on the other hand, has a markedly corrosive action on quartz as evidenced by greatly corroded quartz mosaics noted in the large vitrified xenoliths.

It remains yet to explain the fate of the non-quartzose bands which are essentially of feldspathic composition. The readiness with which feldspathic bands transfuse, as has been noted on vitrified gneissic xenoliths, suggests that such bands may be completely remelted when broken up into small fragments and scattered throughout the basic magma. Even if the resulting syntectic melt is modified by interaction with the magma, it remains essentially feldspathic in its composition, and on crystallization gives rise mainly to feldspar. It appears that the feldspathic xenoliths found in the 1954 Ngauruhoe lava were produced in this way, and that they are also derived from gneiss. The origin of similar feldspathic xenoliths found in the 1919 Ngauruhoe lava is uncertain, according to Battey (1949), but "The absence of quartz seems to negative the possibility of their derivation from either greywacke or ignimbrite."

Thus, the available evidence suggests that the common xenoliths of the 1954 Ngauruhoe lava are of gneissic origin. No xenoliths of Tertiary rocks, greywacke, or rhyolite have been noted. However, advanced vitrification of large gneissic xenoliths testifies that the xenoliths were immersed for a considerable period of time in the magma prior to its extrusion. Evidently the xenoliths were engulfed by the magma at a comparatively great depth. The absence of a chilled margin in the lava at its contact with the xenoliths also points to engulfment at considerable depth. It follows, therefore, that the xenoliths originate from an acid gneiss occurring below the volcano, and underlying the greywacke-argillite basement.

An additional evidence of the presence of metamorphic rocks of high rank beneath the volcanoes is a fragment of thermally metamorphosed schist (P 16865) found by Dr H. J. Harrington (Geological Survey, Wellington) near the summit on Tongariro. The occurrence of such rocks at depth in the centre of the North Island may in future throw new light on the structure of New Zealand.

RARE XENOLITHS

Xenolith of Porphyritic Microdiorite (Porphyrite)

Only one xenolith of porphyritic microdiorite (porphyrite, P 16872) has been noted in the 1954 Ngauruhoe lava (flow of 18/8/54). Its holocrystalline groundmass, consisting of subhedral prismatic plagioclase, subordinate granular pyroxene, a minute amount of quartz, and accessory magnetite, encloses a few micro-phenocrysts of plagioclase. The result of chemical analysis (Table 1, No. 49) indicate an intermediate composition.

The plagioclase is partly vitrified, particularly along the contact between the xenolith and the lava, but minute patches, and fine veinlets of light brown glass penetrate the whole xenolith (Fig. 15). The refractive index of the xenolithic glass is lower, and that of the dark glass of the host lava is higher than the refractive index of Canada balsam.

It may be of interest that Cloud (1951) reported the 1949 Ngauruhoe lava to contain a large number of xenoliths of a coarse-grained andesitic rock.

Intensely Vitrified Granitic Xenolith

One sugary friable xenolith, also found in the lava flow of 18/8/54, has megascopically the appearance of a poorly consolidated coarse sandstone, its grain size not exceeding 1 mm (P 16873). It shows, megascopically, a sharp contact with the enclosing lava. Microscopic examination, nevertheless, reveals a transitional contact, and shows that the inclusion consists of a vesicular, colourless glassy base containing an abundance of highly corroded relics of oligoclase-andesine and quartz, and a small amount of hypersthene which is also corroded. The composition of the plagioclase varies from An 25 to An 38. Magnetite is rare.

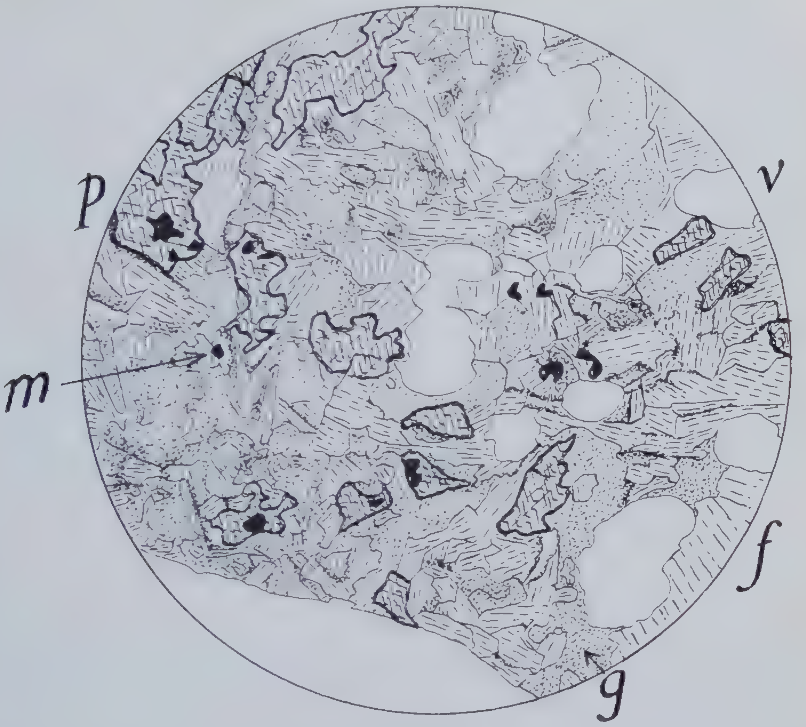


FIG. 15.—Camera lucida drawing of xenolith of slightly vitrified porphyritic microdiorite (porphyrite) found in the flow of 18/8/54 (P 16872). Ordinary light, × 300.

f = feldspar
g = glass
p = pyroxene
m = magnetite
v = vesicle

Drawing, R. C. Brazier.

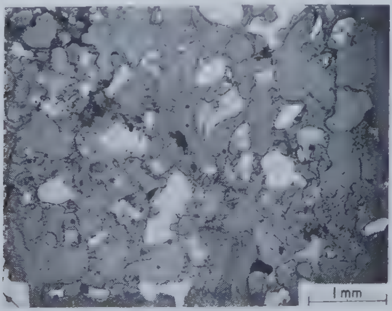


FIG. 16.—Photomicrograph of intensely vitrified granitic xenolith with strongly corroded plagioclase, quartz, and hypersthene, and accessory magnetite surrounded by colourless, vesicular glass (P 16873). Polarized light, × 20. *Photo, A. L. Tilbury.*

Each single crystal relic is completely enclosed by the intervening glass (Fig. 16). Thus, the original textural relationship between the constituent minerals is entirely destroyed. It appears that the glass has formed from a melt resulting from transfusion of plagioclase and reactive solution of quartz. In the most advanced state of corrosion, the glass penetrates along cleavages into the feldspar, which is intensely embayed, and its birefringence greatly reduced due to reheating. No fritting of feldspar has been observed. Thus, the transfusion of this plagioclase contrasts with the transfusion of feldspar noted in highly vitrified xenoliths of acid gneiss, where transfusion is accompanied by fritting of feldspar. Quartz relics are always rounded and transversed by fine cracks, often filled with colourless glass.

The abundance of corroded crystals seems to suggest a vitrified granitic rock rather than a rhyolite or an ignimbrite. It should be also noted that the refractive index of the xenolithic glass, ranging from 1·484 to 1·490, differs notably from the refractive index of the glass of rhyolites and ignimbrites, the latter being, in average, 1·500 ± 0·002.

ASSIMILATION OF GNEISSIC XENOLITHS

Evidence and Dating

The transitional zone between the intensely vitrified gneissic xenoliths and the host lava testifies that the residual magmatic liquid of basic composition and the syntectic acid melt are miscible, at least to a limited extent. The basic character of the plagioclase making up the feldspathic xenoliths, suggests that the interaction between the two melts is reciprocal. From the miscibility relation it follows that the magma was modified by interaction with the syntectic melt of acid composition, i.e., the host magma was contaminated by assimilation of acid gneiss. As this contaminated magma gave rise to a basaltic andesite the magma, prior to its contamination was, of necessity, basaltic in its composition.

As evidenced by the marked proportion of glassy mesostasis, crystallization of the magma was early arrested due to rapid cooling. It appears, therefore, that the transfusion and reactive solution of xenoliths took place before the onset of crystallization, or at a very early stage of it. This dating of assimilation is corroboratory evidence of a deep-seated origin of the gneiss.

As indicated by blebs of augite and hypersthene enclosed in successive zones of some large plagioclase phenocrysts, crystallization of augite has been superseded by precipitation of hypersthene. This succession in the crystallization of pyroxenes, and the continued precipitation of hypersthene seem to be significant. Following Bowen (1928), the early change in crystallization of pyroxenes is considered to have been essentially brought about, or at least facilitated by enrichment of the residual liquid in additional silica and alumina, acquired by assimilation of gneissic xenoliths. If so, the appearance of hypersthene would indicate that assimilation has been operative at an early stage of crystallization.

Reversals of the normal order of zoning, attested by oscillatory zoning of plagioclase phenocrysts, are considered to be due to changes in chemical composition of the residual liquid. Vitrified gneissic xenoliths, invested with a transitional zone, suggest that the compositional changes of the residual liquid were brought about by assimilation. It should be noted that addition of silica and alumina into the magmatic liquid also tend to increase the amount of anorthite in the plagioclase (Bowen, 1928). Thus, the oscillatory zoning seems to indicate that assimilation was operative during crystallization of plagioclase for a prolonged interval of time.

The evidence afforded by the 1954 Ngauruhoe lava and its xenoliths indicates miscibility of the residual magmatic liquid with the syntectic melt of acid composition from an early stage and during a prolonged period of crystallization of the magma. Limitation of miscibility to the latest stage of crystallization was postulated by Holgate (1954) for basic magmas and transfused investment surrounding quartzose xenoliths elsewhere.

Physical Conditions

The xenoliths appear to offer little clue regarding the temperature of the magma at the time of their engulfment. Presence of wollastonite in some gneissic xenoliths suggests that the temperature of the magma did not exceed the inversion temperature of wollastonite to pseudowollastonite, this temperature being 1290°C at 1 atmosphere pressure. No temperature data are available concerning reactive solution of plagioclase in syntectic melts.

It is true that the magma has failed to convert quartz, present in the gneissic xenoliths, into tridymite. However, as shown by Mosesman and Pitzer (1941), quartz is the stable form at moderately high pressures and elevated temperatures and melts directly into liquid without the appearance of any intermediate crystalline phase, at pressures greater than approximately 1160 atmospheres. As the transfusion of gneissic xenoliths occurred at an early stage of crystallization of the magma, i.e., at great depth and pressure and high temperature, the absence of tridymite appears to be due to the prevailing high pressure rather than to inadequate temperature. Ramberg (1952, p. 43) also pointed out that only in the case of low pressure pyrometamorphism would tridymite be able to form under equilibrium conditions by recrystallization.

Extreme vitrification of large gneissic xenoliths, and complete transfusion of feldspathic bands separated from small gneissic xenoliths demonstrate that an adequate amount of heat was available in the magma at the time of engulfment of the xenoliths. As the transfusion of the xenoliths took place at an early stage of crystallization of the magma, and, perhaps, shortly prior to the onset of crystallization, it follows that the heat used for the transfusion and miscibility processes has been partly superheat but mainly heat released during early crystallization.

It is noteworthy that the minute amounts of water in the 1954 Ngauruhoe lava (Table 1, No. 6) and in the large vitrified gneissic xenoliths (Nos 46 to 48) contrast with the vesicular nature of the lava, and particularly with the pumiceous appearance of the xenoliths. It seems that a considerable amount of volatiles was present in both melts prior to congealing. Because volatile-rich silicate melts are known to possess low viscosity, it is inferred that the syntectic melt resulting from the transfusion of gneissic xenoliths and the host magma were rather fluid, and that their low viscosities facilitated the miscibility of these melts and consequently aided the assimilation of acid gneiss.

CONSTANCY OF THE SUM OF ALKALUMINOUS OXIDES—A PETROGENETIC IMPLICATION OF ASSIMILATION

To evaluate the petrogenetic implications of assimilation of acid gneiss a triangular diagram similar to that used by Greig (1927) and Holgate (1954) has been plotted; its vertices are SiO_2, $Al_2O_3 + Na_2O + K_2O$, and $CaO + FeO + MgO$, respectively (Fig. 17). Numbers 1 to 45 on the diagram refer to available chemical analyses of unaltered rocks of the Taupo volcanic association, and numbers 46 to 48 to chemical analyses of intensely vitrified gneissic xenoliths found in the 1954 Ngauruhoe lava. The chemical analyses are listed in Table 1. The analysis of the Maungaongaonga lava (Grange, 1937, p. 67) has not been used because the analysed sample appears to be hydrothermally altered. Instead, the result of a new analysis (No. 22) of an unaltered specimen from the same locality is presented. Unpublished analyses of a hydrothermally altered rhyolite and ignimbrite, occurring at depth at Wairakei, have been also omitted. Data in all diagrams and tables 3 to 5 are based on re-calculated, water-free anlyses.

From the diagram it is evident that most of the points representing the rocks of the Taupo volcanic association are aligned parallel to the side of the triangle opposite the alkaluminous corner ($Al_2O_3 + Na_2O + K_2O$). Exceptions are basic lavas, Nos 4, 5, 7, 11, 12, and 13, belonging to the accumulative series, which, as shown in the following section, differ in their origin from the remaining rocks, and will not be considered in the meantime.

The alignment indicates that the sum of alkaluminous oxides ($Al_2O_3 + Na_2O + K_2O$) remains approximately constant through the whole volcanic association, excepting the basic lavas of the accumulative series. On the other hand, the cafemic oxides ($CaO + FeO + MgO$) and SiO_2 vary continuously over a wide range. Table 3 shows that the greatest value of the sum of alumina, soda, and potash amounts to

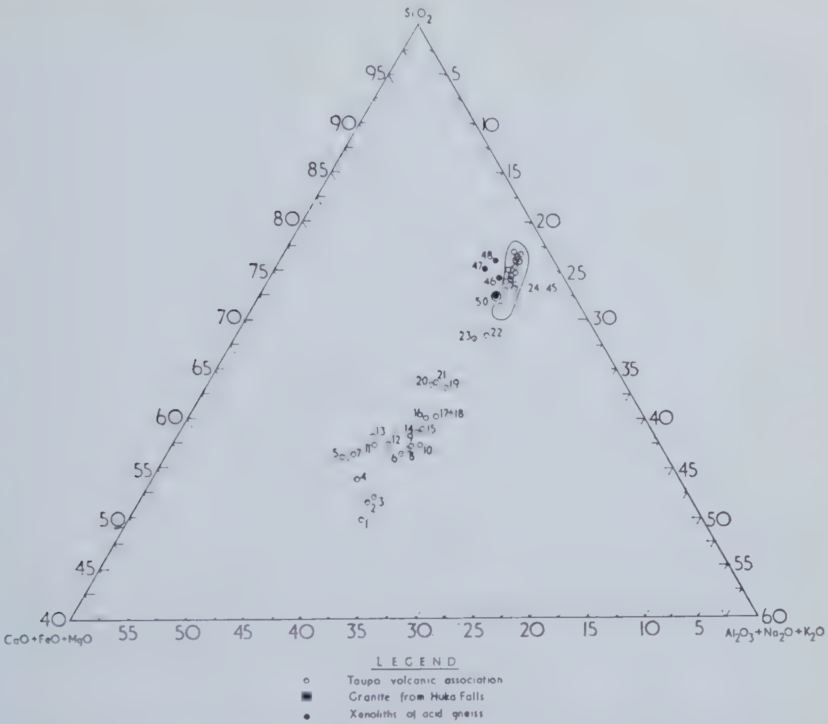


FIG. 17.—Triangular plot with vertices SiO_2, $Al_2O_3 + Na_2O + K_2O$ and $CaO + FeO + MgO$, as used by Greig (1927) and Holgate (1954), showing the constancy of the sum of alkaluminous oxides, characteristic of the Taupo volcanic association.

22·1% and the least value to 19·54%, the mean value being 20·95%. The standard deviation is 0·58.

Thus, the constancy of the sum of alkaluminous oxides appears to be a characteristic feature of the magmatic differentiation that produced the Taupo volcanics. This constancy indicates that magmatic differentiation has brought about variation in silica and cafemic oxides but no enrichment of alkaluminous oxides, though alumina, soda, and potash may vary individually to a limited extent. However, it should be stressed that enrichment in alkaline feldspar molecules, i.e., essentially in alkaluminous oxides, is required by the theory of fractional crystallization (Bowen, 1928). The constancy of the sum of alkaluminous oxides leads, therefore, to the important conclusion that the rocks of the Taupo volcanic association, with the exception of the accumulative series, have been derived either by magmatic differentiation other than fractional crystallization, or not solely by fractional crystallization.

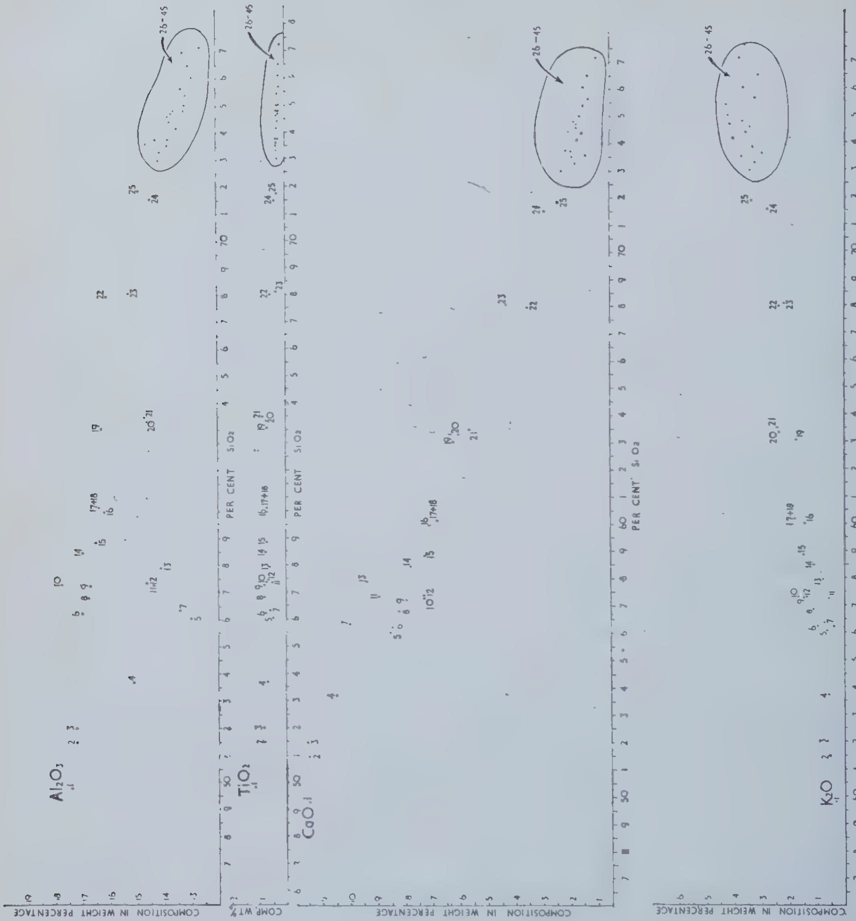
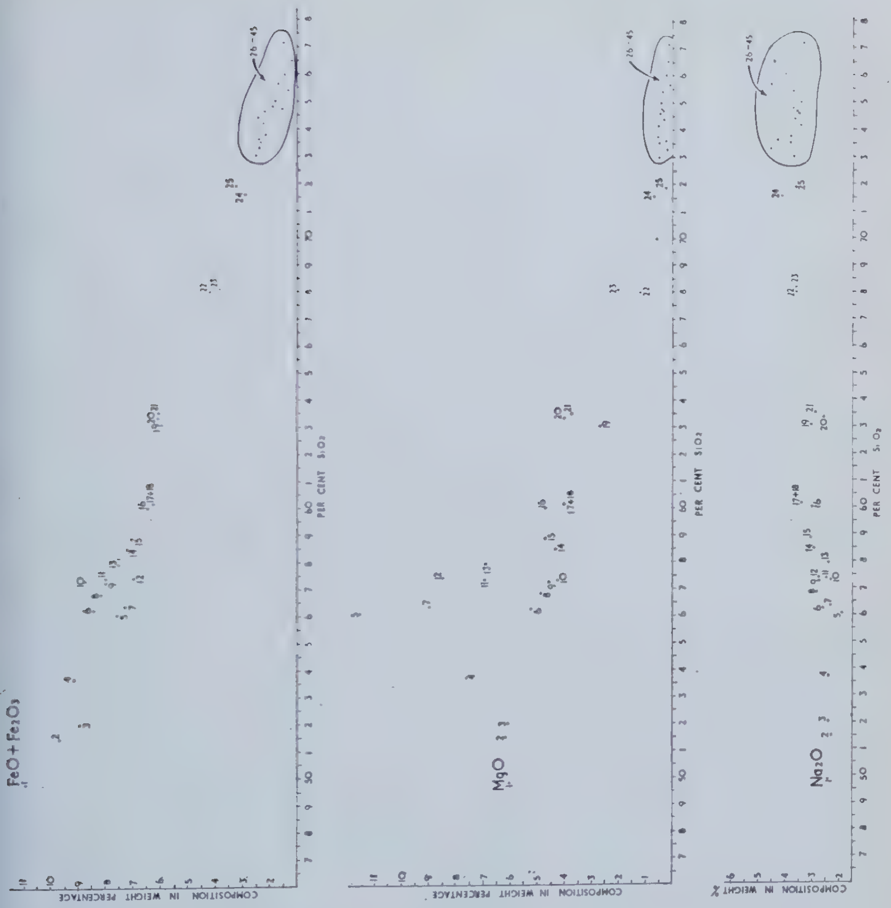


Fig. 18.—Variation diagram of the Taupo volcanic asso-
tion at the basic end; (2) scarcity of volcanics with
71%; (3) conspicuous break in variation of MgO
tion of Na_2O and K_2O throughout the acid volcanics.

The presence of highly vitrified xenoliths of acid gneiss in the 1954 Ngauruhoe lava, and particularly the development of a transitional zone at the contact between the xenoliths and the lava suggest strongly that assimilation has been an important petrogenetic process. It should also be noted that, excepting the accumulative series, the lavas of the basalt-dacite range and, similarly, the acid volcanics display continuous variation (Fig. 18), indicating operation of fractional crystallization. It appears, therefore, that assimilation has been operative in conjunction with fractional crystallization. These processes, acting together,



ciation showing: (1) discontinuous irregular varia-
a silica content between approximately 64% and
at about 68% SiO_2; (4) complex trend in varia-

seem to be primarily responsible for the derivation of the Taupo volcanics, with the exception of the rocks of the accumulative series.

The operation of assimilation in conjunction with fractional crystallization is in agreement with the view expressed lately by several workers concerning the petrogenesis of the rocks of calcalkaline series. They question that these rocks are produced essentially by fractional crystallization alone (Wager and Deer, 1939; Tilley, 1951; Barth, 1952; Holgate, 1954; and Poldervaart and Elston, 1954).

The sum of alkaluminous oxides of rocks from the Katmai (Fenner, 1926) and Lassen regions (Williams, 1932) have also been plotted in

TABLE 3.—Amounts of SiO_2, $Al_2O_3 + Na_2O + K_2O$, and $CaO + MgO + FeO$ of the rocks of the Taupo Volcanic Association.

Chemical analysis No.	SiO_2	$Al_2O_3 + Na_2O + K_22O$	$CaO + MgO + FeO$
1	49·79	20·25	29·95
2	51·47	20·06	28·47
3	51·98	20·28	27·71
4	53·68	18·09	28·24
5	56·03	15·58	28·37
6	56·23	20·63	23·13
7	56·34	16·51	27·17
8	56·83	20·79	22·37
9	57·24	20·98	21·75
10	57·27	21·72	21·00
11	57·34	17·68	24·97
12	57·36	18·85	23·78
13	57·93	17·34	24·73
14	58·47	21·13	20·41
15	58·86	21·10	20·04
16	60·02	20·69	19·29
17	60·15	21·67	18·17
18	60·16	21·53	18·21
19	63·04	21·13	15·83
20	63·33	19·54	17·11
21	63·48	20·03	16·49
22	68·00	22·10	9·73
23	68·09	21·14	10·76
24	71·55	21·38	7·06
25	71·87	21·82	6·30
26	72·99	21·26	5·74
27	73·27	21·90	4·82
28	73·52	21·34	5·14
29	73·58	21·90	4·50
30	73·74	21·06	5·19
31	73·77	21·03	5·20
32	74·16	20·96	4·87
33	74·38	20·95	4·66
34	74·60	20·69	4·72
35	74·69	21·33	3·97
36	74·77	20·93	4·30
37	74·81	20·62	4·56
38	74·97	20·98	4·05
39	74·97	20·69	4·33
40	75·39	21·10	3·51
41	75·64	21·02	3·34
42	76·07	20·55	3·38
43	76·49	20·55	2·94
44	77·14	20·04	2·82
45	77·15	19·98	2·87

Fig. 19. The diagram shows that the sum of these three oxides also remains practically constant for each volcanic series, though this petrochemical index seems to vary from one region to the other. It may be of interest that the alkali-lime index of the Taupo volcanic association (64·0) comes very close to the corresponding value of the Katmai region, 63·5 (Peacock, 1931) and to that of the Lassen region,

63·9 (Williams, 1932). Accordingly, all three regions are classified as calcic. Thus, it appears that the constancy of the sum of alkaluminous oxides may generally hold for rocks of calcic series. This would exclude the possibility that the constancy of the sum of alkaluminous oxides is a fortuitous result of fractional crystallization of the Taupo volcanic association. Evidently, this sum is also a characteristic petrogenetic index.

The constancy of the sum of alkaluminous oxides differentiates the Taupo volcanics from the rocks of the olivine basalt-trachyte association of other regions, as evidenced by the Hawaiian rocks (Macdonald, 1949). Table 4 and Fig. 19 show that the rocks of the olivine basalt-trachyte association are characterized by a considerable variation in the sum of alkaluminous oxides. It should be also noted that the olivine basalt-trachyte association is generally considered to be derived by fractional crystallization of an uncontaminated basaltic magma.

TABLE 4.—Amounts of SiO_2, $Al_2O_3 + Na_2O + K_2O$, and $CaO + MgO + FeO$ of the Hawaiian Olivine Basalt-Trachyte Association.

Chemical analysis No.	SiO_2	$Al_2O_3 + Na_2O + K_2O$	$CaO + MgO + FeO$
1	36·73	15·57	44·83
2	38·66	15·97	44·01
3	39·44	14·12	44·17
4	41·26	14·38	43·29
5	43·36	13·75	42·19
6	45·00	18·93	35·30
7	45·30	14·84	39·10
8	46·74	10·28	42·79
9	48·35	16·18	34·74
10	48·76	21·90	28·54
11	50·44	17·06	31·81
12	51·35	23·29	25·11
13	62·77	28·05	7·49

EFFECT OF ASSIMILATION ON MAGMATIC DIFFERENTIATION OF THE TAUPO VOLCANIC ASSOCIATION

Differentiation of Basaltic Magma

To find out the magmatic relationship of the rocks belonging to the Taupo volcanic association, a variation diagram, similar to that used by Harker (1909) and Bowen (1928), has been plotted (Fig. 18). The numbers 1 to 45 on the diagram refer also to chemical analyses listed in Table 1.

An outstanding feature immediately apparent from this diagram is discontinuous irregular variation at the basic end, shown by considerable scattering of points between approximately 56% and 59% SiO_2. If

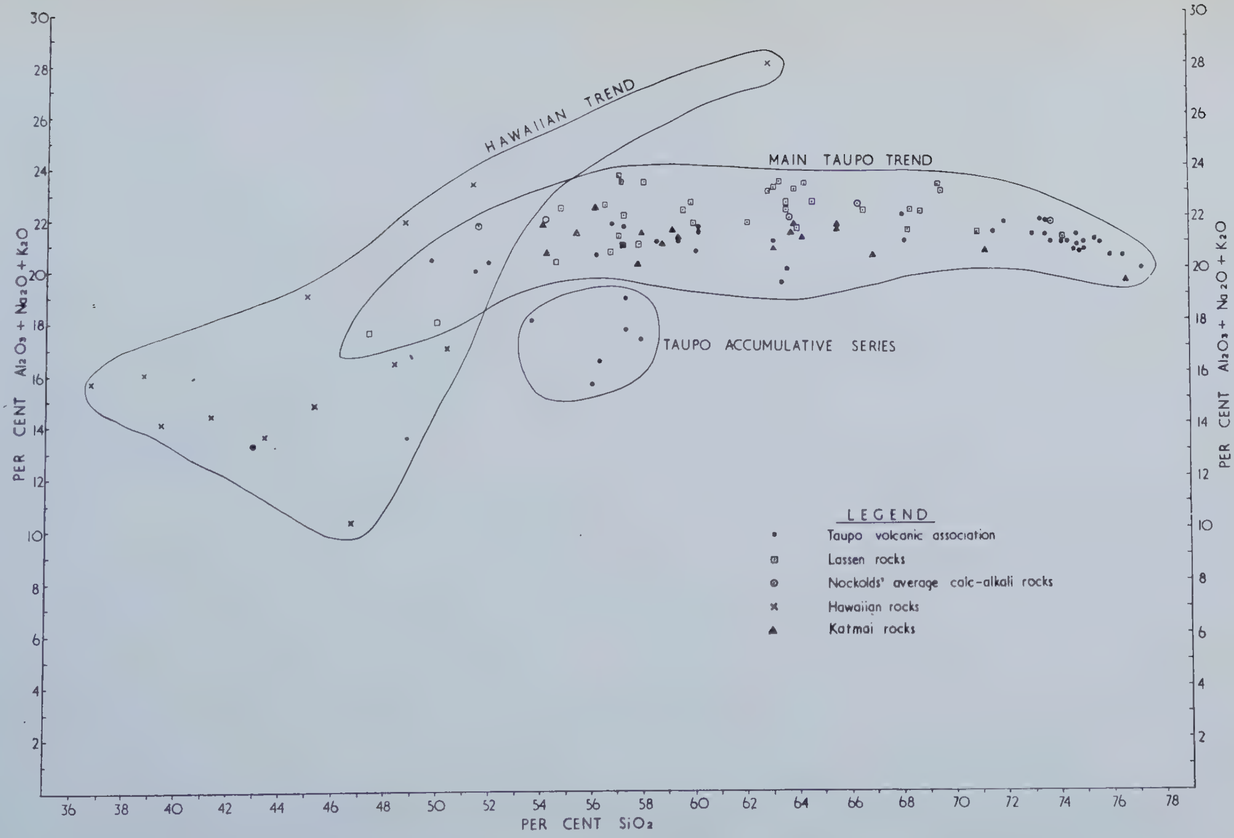


FIG. 19.—Diagram showing the constancy of the sum of alkaluminous oxides of the Taupo volcanics, the Katmai and Lassen rocks, and Nockolds' average calc-alkaline rocks as contrasted with the Hawaiian olivine basalt-trachyte association characterized by considerable variation of the sum of alkaluminous

the lavas Nos 4, 5, 7, 11, 12, and 13, causing the scatter, are neglected, than the remaining rocks up to 68% SiO_2, to be named the main basic series, show continuous variation. The aberrant rocks will be referred to as to the accumulative series.

The main basic series consists of basalts and basaltic andesites, containing a small amount of olivine; pyroxene andesites, characterized by hypersthene and augite; and dacites in which hornblende may occur in addition to hypersthene. The basalts and basaltic andesites of the accumulative series, on the other hand, are characterized by a notable amount of olivine phenocrysts.

Continuous variation, characteristic of the main basic series, indicates a liquid line of descent (Bowen, 1928). As the lavas of the accumulative series are well separated from the main basic series, the former are evidently of an origin different from that of the main basic series. This difference is well demonstrated by the AFM diagram (Fig. 20), where

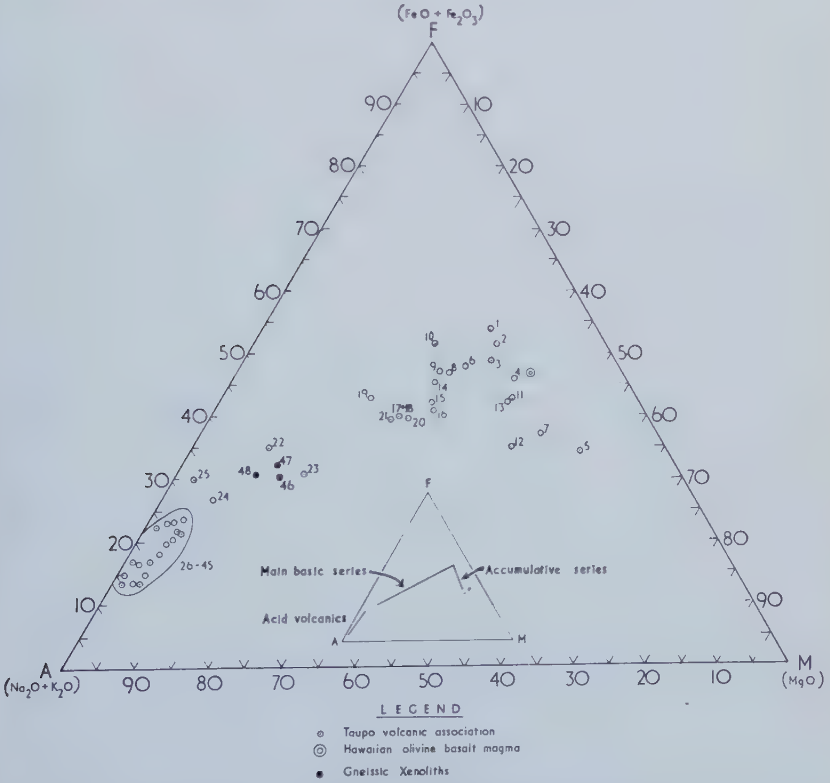


FIG. 20.—(a) A-F-M diagram showing enhanced basic character of the rocks of the accumulative series in relation to the rocks of the main basic series and acid volcanics. (b) The trends of magmatic differentiation of the Taupo volcanic association are shown in the inset.

the rocks of the accumulative series appear to be more basic than the Hawaiian primary magma, the non-volatile fraction of this magma having the composition of olivine basalt (Macdonald, 1949). The trends of magmatic differentiation that produced the rocks of the Taupo volcanic association are shown in the inset of Fig. 20.

The enhanced basic character of the rocks of the accumulative series, characterized by numerous olivine phenocrysts, suggests that gravitational crystal accumulation was an important process in the production of these rocks. It seems that varying amounts of early crystallized olivine accumulated in the magmatic liquid, most likely together with varying amounts of augite and basic plagioclase. The suggestion is made that the magmatic liquid, subsequent to its enrichment in crystalline phases due to gravitational accumulation of early separated crystals, was affected by fractional crystallization. Thus, crystal accumulation combined with fractional crystallization produced the rocks of the accumulative series.

The basalts and basaltic andesites of the main basic series, characterized by high content of alumina, and evidently derived from an alumina-rich magma, contrast with the basic lavas of the accumulative series which are low in alumina, high in magnesia, and commonly also show an excess of lime. These chemical characteristics as well as abundance of olivine, indicate affinities between the rocks of the accumulative series and the olivine basalt magma of the Hawaiian type, which is poor in alumina but rich in magnesia (Macdonald, 1949). It follows, therefore, that the rocks of the accumulative series may be derived from a magma, its non-volatile fraction having the composition of olivine basalt.

If a different magma is postulated for each basic series then the question arises concerning the relationship between these two magmas. As evidenced by the 1954 Ngauruhoe lava and its xenoliths, basaltic magma was contaminated by assimilation of acid gneiss. It is concluded, therefore, that the alumina-rich parent magma of the main basic series was produced by contamination of a primary basaltic magma with acid gneiss. The evidence is inconclusive whether the hypersthene andesite from the White Island volcano (Nos 20 and 21) has been derived from the primary magma of olivine basalt composition or from the contaminated parent magma.

The contaminated parent magma may be safely assumed to approximate in its composition to that of the least siliceous rock of the main basic series. Accordingly, the K-Trig basalt (Table 1, No. 1) would represent the non-volatile fraction of the contaminated parent magma. Instead of the least siliceous lava it may be justified to take the average of the first three analyses (Nos 1 to 3) because they show only negligible variation except in $FeO + Fe_2O_3$ and SiO_2, the latter varying approximately by 2·2% only.

The next step is to enquire into the composition of the uncontaminated primary magma. Thus, the problem is to find out the possible compositions of the magmatic material, which added to acid gneiss (Table 5, column 1) would yield a rock substance having the averaged composition of analyses Nos 1 to 3 (Table 5, column 2). This has been done graphically in Fig. 21.

The composition of the most basic material to be added to acid gneiss to give the average composition of Nos 1 to 3 is shown in column 3 of Table 5. No potash is present in this material, but all available evidence indicates that primary basaltic magma contains potash. A potash-bearing composition is therefore postulated. Arbitarily, the amount of 0·4% K_2O may be assumed, this value being intermediate between the average amount of K_2O in analyses Nos 1 to 3, and the potash content of the Hawaiian primary uncontaminated magma. The composition of the graphically determined uncontaminated magma containing 0·4% K_2O would be as shown in column 4 of Table 5. This hypothetical primary magma would be required to assimilate 9·8% by weight of acid gneiss in its entirety, to produce the contaminated magma having the average composition of Nos 1 to 3.

In comparing the derived magmatic composition with the Hawaiian primary magma (column 5 of Table 5) it can be seen that they are not in agreement. The determined magmatic composition is markedly deficient in MgO and TiO_2, but its amounts of K_2O and $FeO + Fe_2O_3$ are only negligibly below the respective values for the Hawaiian primary magma. However, the hypothetical magma shows a marked excess of Al_2O_3 and CaO, the amounts of SiO_2 and Na_2O being only slightly higher than in the Hawaiian primary magma.

It may be, however, that the analysed gneissic xenoliths were altered to some extent by reaction with the enclosing magma. If so, the chemical analyses do not give the true composition of the unaltered acid gneiss. Therefore, the magmatic composition, as derived graphically, may be somewhat distorted and represents only a rough approximation to the uncontaminated primary magma of the Taupo volcanic zone.

Nevertheless, from the discrepancy noted between the primary Hawaiian magma and the derived magmatic composition it may be inferred that either:

(a) The uncontaminated primary basaltic magma of the Taupo volcanaic zone has a somewhat different composition from the Hawaiian parent magma, or,

(b) the acid gneiss was assimilated by the primary magma of olivine basalt composition not in its entirety, but selectively.

Another possibility is that the parent magma of the main basic series represents the residual magmatic liquid resulting from the removal of early formed crystals from the primary magma of olivine basalt composition. This residual liquid would be enriched in alumina and deficient in magnesia. It may also have been contaminated by assimila-

TABLE 5.

	1	2	3	4	5
SiO_2	75·25	51·08	43·4	49·0	48·35
TiO_2	0·19	0·93	1·3	1·1	2·77
Al_2O_3	14·87	17·29	18·2	17·6	13·18
Fe_2O_3 FeO	2·29	9·85	12·4	10·6	11·43
MgO	0·97	6·11	7·6	6·4	9·72
CaO	2·10	11·50	14·4	12·2	10·34
Na_2O	1·99	2·40	2·8	2·7	2·42
K_2O	2·22	0·50	0·0	0·4	0·58

1. Gneiss (averaged chemical analyses Nos. 46 to 48).
2. Contaminated basaltic parent magma (averaged chemical analyses Nos. 1 to 3).
3. Most basic composition of magma giving with acid gneiss the contaminated basaltic parent magma (see Fig. 21).
4. Possible composition of magma containing 0·4% K_2O, and giving with acid gneiss the contaminated basaltic parent magma.
5. Hawaiian parent magma (Macdonald, 1949).

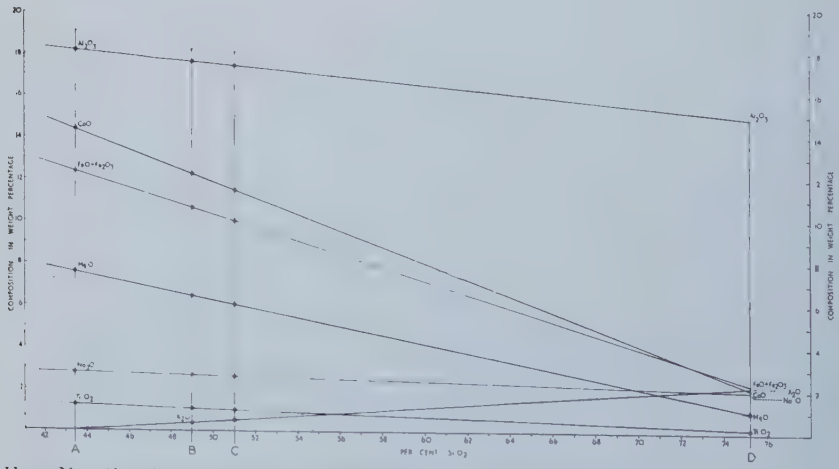


FIG. 21.—Graph showing the composition of magmatic material which, if added to acid gneiss, would yield the contaminated basaltic parent magma.
A = most basic magma
B = basic magma with 0·4% K_2O
C = contaminated parent magma (averaged analyses Nos 1 to 3)
D = acid gneiss (averaged analyses Nos 46 to 48)

tion of acid gneiss. The present evidence does not reveal whether this actually occured or not.

If selective assimilation was operative, as favoured by the writer, then by comparing columns 2 and 5 of Table 5, it becomes immediately evident that the uncontaminated primary magma of Hawaiian type, essentially olivine basalt in composition, took up into solution from the acid gneiss SiO_2, Al_2O_3 and CaO. It also seems that small amounts of Na_2O and K_2O were acquired by assimilation. This is somewhat concealed by the data in Table 5 because the added proportion of Na_2O and K_2O, being markedly less than the added proportion of SiO_2 and Al_2O_3, has the effect of decreasing the percentage of Na_2O and K_2O in the contaminated parent magma (column 2 of Table 5). Thus, selective assimilation of alumina and alkalies in addition to silica and lime is characteristic of the parent magma which produced the main basic series controlled by the constancy of the sum of alkaluminous oxides. It should be stressed that the sum of the alkaluminous oxides remains constant during magmatic differentiation in spite of addition of these oxides to the magma by selective assimilation of acid gneiss.

No effect of selective assimilation of lime on magmatic differentiation has been noted. Nevertheless, selective assimilation of alkaluminous oxides and silica is, in its effect on magmatic differentiation, similar to that of fractional crystallization, both processes producing an enrichment of the magma in these constituents.

Therefore, the effect of selective assimilation may be generally distinguished from that of fractional crystallization only with great difficulty. It seems that it is the constancy of the sum of alkaluminous oxides that provides a reliable diagnostic criterion of selective assimilation.

Magmatic Relationship Between Acid Volcanics and Rocks of the Basalt-Dacite Range

In testing the magmatic relationship between the acid volcanics and the rocks of the basalt-dacite range, it should be noted that only two chemical analyses (Nos *22* and *23*, Table 1) are available of lavas intermediate between the pyroxene andesites and the rhyolitic rocks, i.e., between approximately 64% and 71% SiO_2. These two lavas are dacites containing 68% SiO_2. Pyroxene is the only ferromagnesian mineral found in a core of Maungaongaonga dacite (No. *22*), but hornblende and hypersthene besides varying amounts of augite and rare biotite occur in the Tauhara dacite (No. *23*) according to Grange (1937).

It should be stressed that the shortage of chemical analyses of rocks ranging between 64% and 71% SiO_2 reflects the striking scarcity of such rocks in the Taupo volcanic zone. Only a few outcrops of rocks in this silica range are known. Recently, the geology of the area has been extensively surveyed in connection with the construction of dam sites, geothermal steam investigation, and search for raw material for perlite manufacture. It seems to be very unlikely that, if such rocks occur in an appreciable volume, they should have escaped the attention of geologists.

Nor has extensive drilling for geothermal steam, to maximum depth of 4,020 ft, shown that lavas or their plutonic equivalents containing 64% to 71% SiO_2 occur below the surface in the vertical range explored. But drilling has revealed that granite may occur at great depth. This is inferred from granitic boulders found between 33 and 118 ft below the surface at the Huka Falls. The chemical composition of the granitic boulders corresponds to that of plagioclase rhyolite, this being the composition of the acid volcanics of the Taupo volcanic zone (Table 1, No. 50). However, a great volume of granodiorite would be required to make up for the deficiency in dacites. Thus, all the available evidence indicates that lavas intermediate in composition between the pyroxene andesites and the rhyolitic rocks have been rarely extruded.

The scarcity of dacites, the consistent absence of lavas with a silica content approximately between 68% and 71%, the conspicuous break in variation of MgO at about 68% SiO_2, and the complex trend in variation of Na_2O and K_2O throughout the acid volcanics seem to be related phenomena of petrogenetic significance. They suggest the end of fractional crystallization of the main basic series at 68% SiO_2.

Fractional crystallization of a basaltic magma modified by assimilation of acid gneiss would be expected, according to some petrologists, (Bowen, 1928; Tilley, 1951) to produce a large volume of residual liquids of intermediate and acid composition than would an uncontaminated basaltic magma. Therefore, the scarcity of dacites may, at first, appear to be at variance with the result expected from fractional crystallization of basaltic magma contaminated by acid gneiss.

Nevertheless, fractional crystallization of the parent magma of the main basic series, modified by selective assimilation of acid gneiss, has been shown to proceed in such a way that the sum of alkaluminous oxides remains constant, and residual liquids are not enriched in these oxides even at more progressive stages of fractionation. It appears that selective assimilation, due to intervention of the petrochemical constancy concerning the alkaluminous oxides, is an impedance to fractional crystallization, and retards its progress, causing a greater volume of less differentiated rocks, i.e., pyroxene andesites, to be produced than in the case of an uncontaminated basaltic magma. Thus, only a small volume of the very last differentiates may be expected. It is concluded, therefore, that the dacites, containing about 68% SiO_2, and occurring in comparatively small volume, are not intermediate rocks between the pyroxene andesites and the acid volcanics, but are the last differentiates of the modified magma of the main basic series. They are the analogues of trachytes, the end product of fractional crystallization of the primary uncontaminated basaltic magma. Further, it follows that the more voluminous pyroxene andesites represent the true intermediate rocks of the series ranging from basalts to dacites.

In accepting the dacites as the last differentiates of the contaminated basaltic magma, all the remaining more acid rocks of the Taupo volcanic association are excluded from being derived from this parent magma. The enormous volume of these acid volcanics extruded in the Taupo volcanic zone contrasts sharply with the much less voluminous basalts, basaltic andesites, pyroxene andesites, and the scanty occurrence of dacites. But fractional crystallization of uncontaminated basaltic magma may produce approximately only 5% of granitic liquid (Barth, 1952) and fractional crystallization of basaltic magma contaminated by selective assimilation of acid gneiss leads ultimately to evolution of a small volume of dacites. The volume relationship between the acid volcanics and the basalts testifies that the former were not derived from a basaltic magma. It is concluded that the rocks of the Taupo volcanic association belong not to one continuous series but to two distinct groups of different magmatic origin:

(1) the lavas of the main basic series and the accumulative series are of basaltic origin, and

(2) the acid volcanics are derived from a magma of rhyolitic composition.

The acid volcanics, ranging between 71·5% and 77% SiO_2, consist of rhyolites, ignimbrites, vitric tuffs (ash showers), and unconsolidated pumiceous deposits presumably of nuée ardente origin (Baumgart and Healy, 1956). These glassy or devitrified rocks have the composition of a plagioclase rhyolite, the hypersthene-plagioclase assemblage being characteristic. The plagioclase varies in composition from oligoclase to andesine.

It should be pointed out that in their chemical composition the rhyolites and ignimbrites (Table 1, Nos 24 to 45) are conspicuously similar to the vitrified gneissic xenoliths (Table 1, Nos 46 to 48), and that these large gneissic xenoliths were greatly re-melted by basic magma, and small feldspathic fragments of gneissic origin were completely transfused by this magma. These facts suggest that the rhyolites and ignimbrites may be derived from an acid magma resulting from transfusion of acid gneiss in prolonged contact with basaltic magma at great depth. This line of evidence leads to the postulation of two parent magmas for the Taupo volcanic association—one basaltic magma and one syntectic magma of rhyolitic composition.

Both the triangular plot (Fig. 17) and the diagram (Fig. 19) show that the constancy of the sum of alkaluminous oxides also holds for the rhyolites and ignimbrites derived from the syntectic acid magma. The constancy of the sum of alkaluminous oxides suggests that the rhyolitic magma was contaminated to some extent by basaltic magma, this being in accord with the demonstrated miscibility relationship between the syntectic melt and the basaltic magma. Continuous variation displayed by the acid volcanics (Fig. 18), though of a peculiar type, undoubtedly indicates that fractional crystallization was operative, but from the constancy of the sum of alkaluminous oxides it is inferred that this process was effective to a limited extent only. Thus, it appears that the constancy of the sum of alkaluminous oxides is a controlling factor of fractional crystallization of both the contaminated basaltic magma and the syntectic magma of rhyolitic composition.

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TEMPERATURE DISTRIBUTION ABOUT A COOLING VOLCANIC INTRUSION

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Summary

Temperature distributions are derived for the conductive transfer of heat from a vertical volcanic feeding dyke or pipe of radius a, injected into a rock mass of thermal diffusivity χ which has an initial steady-state temperature distribution due to an underlying magmatic layer of constant temperature at depth h. The temperature at a distance x from the centre of the intrusion and a depth z below the surface is found when the dyke or pipe has cooled for time t after injection. Results are expressed in terms of the parameters $\xi = x/h$, $\alpha = a/h$, $\zeta = z/h$, and $\tau = \sqrt{\chi t}/h$; and numerical results, including graphs of the surface thermal gradient and of the temperature at the centre of the dyke or pipe, are given for $\alpha = 0{\cdot}01$, $0 \leqq \xi \leqq 0{\cdot}30$, $0{\cdot}01 \leqq \zeta \leqq 0{\cdot}80$, and $0{\cdot}001 \leqq \tau \leqq 0{\cdot}050$.

Introduction

Volcanism essentially involves an intensive discharge of the earth's internal heat through a restricted channel in the crust; and one form of this discharge is the conduction of heat from the magma which fills volcanic vents. The purpose of this paper is to derive the theoretical temperature distribution following the injection of magma into two types of volcanic vent—a vertical plane dyke, and a vertical cylindrical pipe—assuming that the magma cools until the pre-existing temperature distribution is re-established.

Two specific properties of the temperature distribution of practical importance are the vertical thermal gradient at the surface of the ground, and the temperature at the centre of the cooling intrusion; numerical examples are shown in graphical form in Figs 2 to 5. The surface thermal gradient can readily be measured in drillholes; in New Zealand a number of such measurements have already been made in the volcanic region of the North Island (Banwell, 1955). A knowledge of the temperature at the centre of a cooling intrusion is of value in any study of the mechanism of volcanic eruptions.

The Physical Model

Properties of the Model

If any geological process is to be studied by mathematical means, the first step is to construct a physical model whose properties, while

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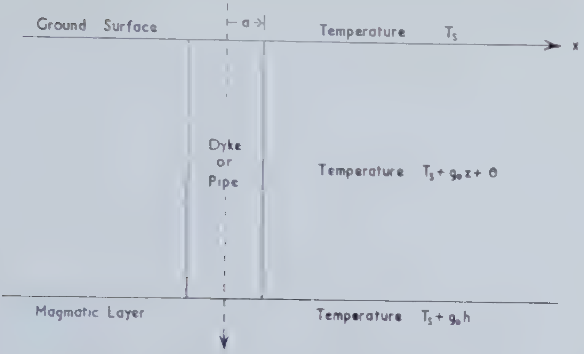

FIG. 1.—Diagram of volcanic dyke or pipe.

corresponding as far as possible to the geological conditions, are of necessity much simplified. Such a theoretical model (Fig. 1) has been constructed on the following assumptions:

(a) That the transfer of heat is purely conductive. Loss of heat from the injected magma in escaping gases undoubtedly occurs, but should only affect the temperature distribution close to the surface vent.

(b) That the thermal properties of the rock are constant throughout.

(c) That the area to be considered is underlain by a magmatic layer of constant temperature.

(d) That the ground surface is flat.

(e) That the temperature at the surface of the ground is constant. Seasonal variations of the ground surface temperature will influence measured surface thermal gradients; this effect has been discussed by Van Orstrand (1951).

(f) That before the magma is injected into the dyke or pipe, the temperature distribution in the ground is linear with depth, being due solely to heat flow from the underlying magmatic layer.

(g) That the injection of the magma is instantaneous.

(h) That the temperature of the injected magma at the time of injection varies linearly with depth, being equal, at the bottom of the dyke or pipe, to the temperature of the underlying magmatic layer. (This includes the case where the temperature is constant with depth.)

Notation

The rock and the injected magma in the region $x \geqq 0$, $0 \leqq z \leqq h$ (in rectangular co-ordinates for the dyke, or cylindrical for the pipe) is assumed to have a thermal conductivity k, heat capacity c, density σ, and thermal diffusivity $\chi = k/c\sigma$.

If the ground surface is at a constant temperature T_s, and the vertical thermal gradient due to the underlying magma at depth h is g_0, then the temperature T at any point before injection is

$$T = T_s + g_0 z \qquad \text{............} \quad (1)$$

and the temperature at any point after injection is

$$T = T_s + g_0 z + \theta \tag{2}$$

where θ is the additional temperature due to the injection. The dyke or pipe bounded by $x = a$ is injected with magma having initially a constant vertical thermal gradient g_m; the initial temperature within the intrusion is

$$T_0 = T_s + g_0 h - g_m(h - z) \tag{3}$$

and from (2) and (3) the initial value of θ within the intrusion is

$$\theta_0 = \gamma_0 (h - z) \tag{4}$$

where $\gamma_0 = g_0 - g_m$.

The vertical thermal gradient at the surface of the ground is given by

$$g_s = (dT/dz)_{z=0} = g_0 + \gamma_s \tag{5}$$

where $\gamma_s = (d\theta/dz)_{z=0}$.

The temperature at the centre of the dyke or pipe is

$$T_c = T_s + g_0 z + \theta_c \tag{6}$$

where θ_c is the value of θ at $x = 0$.

TEMPERATURE DISTRIBUTION ABOUT A COOLING INTRUSION

The temperature T at any point must satisfy the Fourier conduction equation (Carslaw and Jaeger, 1947).

$$\partial T/\partial t = \chi \nabla^2 T(x, z, t) \tag{7}$$

From (2) and (7), θ must satisfy

$$\partial \theta/\partial t = \chi \nabla^2 \theta(x, z, t) \tag{8}$$

and the boundary conditions in the region $x \geqq 0, 0 \leqq z \leqq h, t \geqq 0$.

$$\left.\begin{array}{llll}
\text{(i)} & z = 0 & & \theta = 0 \\
\text{(ii)} & z = h & & \theta = 0 \\
\text{(iii)} & x = 0 & & d\theta/dx = 0 \\
\text{(iv)} & x \to \infty & & \theta \to 0 \\
\text{(v)} & t = 0 & 0 \leqq x \leqq a & \theta = \gamma_0 (h - z) \\
 & & x > a & \theta = 0
\end{array}\right\} \tag{9}$$

The conduction equation (8) may be solved by the use of integral transform methods (Sneddon, 1951; McLachlan, 1948; Erdélyi, 1954), and the solutions are conveniently expressed in terms of the dimensionless parameters

$$\xi = x/h$$
$$\alpha = a/h$$
$$\zeta = z/h$$
$$\tau = \sqrt{\chi t}/h$$

The general form of the solution is

$$\theta(\xi, \zeta, \tau) = (\gamma_0 h)\, \Xi(\xi, \tau)\, Z(\zeta, \tau) \qquad \text{..........} \quad (10)$$

where, for the dyke

$$\Xi_d(\xi, \tau) = \operatorname{erf}\{(\alpha - \xi)/2\tau\} + \operatorname{erf}\{(\alpha + \xi)/2\tau\} \qquad \text{..........} \quad (11)$$

and for the pipe

$$\Xi_p(\xi, \tau) = (1/\tau^2) \exp(-\xi^2/4\tau^2) \int_0^\alpha \exp(-\lambda^2/4\tau^2)\, I_0(\xi\lambda/2\tau^2)\, \lambda\, d\lambda \qquad \text{..........} \quad (12)$$

and in both cases

$$Z(\zeta, \tau) = \sum_{n=1}^{\infty} (1/n\pi) \exp(-n^2\pi^2\tau^2) \sin(n\pi\zeta) \qquad \text{..........} \quad (13)$$

The contribution to the surface thermal gradient by the intrusion is

$$\gamma_s = \gamma_0\, \Xi(\xi, \tau)\, Z'(0, \tau) \qquad \text{..........} \quad (14)$$

where

$$Z'(0, \tau) = \sum_{n=1}^{\infty} \exp(-n^2\pi^2\tau^2) \qquad \text{..........} \quad (15)$$

and the additional temperature at the centre of the intrusion is

$$\theta_c = (\gamma_0 h)\ \Xi(0, \tau)\, Z(\zeta, \tau) \qquad \text{..........} \quad (16)$$

where for the dyke

$$\Xi_d(0, \tau) = 2\,\mathrm{erf}(a/2\tau) \qquad \text{.........} \quad (17)$$

and for the pipe

$$\Xi_p(0, \tau) = 2\{1 - \exp(-a^2/4\tau^2)\} \qquad \text{.........} \quad (18)$$

RESULTS

A number of the functions derived above have been computed for values of the parameters

$$a = 0{\cdot}01,\ 0 \leqq \xi \leqq 0{\cdot}30,\ 0{\cdot}01 \leqq \zeta \leqq 0{\cdot}80,\ 0{\cdot}001 \leqq \tau \leqq 0{\cdot}050.$$

Table 1 gives values of $\Xi_d(\xi, \tau)$; Table 2 gives values of $\Xi_p(\xi, \tau)$; and Table 3, values of Z (ζ, τ) and Z' $(0, \tau)$. (The tables of Ξ (ξ, τ), which have been computed for $a = 0{\cdot}01$, may be used for values of $a = k \times 0{\cdot}01$ by replacing ξ and τ by $k\xi$ and $k\tau$.) The tables enable the temperature at any point (equations 2 and 10) to be readily obtained.

From these values, graphs have been constructed of the surface thermal gradient for the cooling dyke in Fig. 2 and for the cooling pipe in Fig. 3; and for the temperature at the centre of a cooling dyke in Fig. 4 and of a cooling pipe in Fig. 5. It was assumed that the initial temperature of the intrusion was constant with depth, i.e., $g_m = 0$ and $\gamma_0 = g_0$; and that $h = 10$ km, $a = 0{\cdot}1$ km, and the thermal diffusivity $\chi = 0{\cdot}01$ cm^2/sec. The surface thermal gradient is expressed as

$$g_s/g_0 = 1 + \Xi(\xi, \tau)\ Z'(0, \tau)$$

and the temperature at the centre of the intrusion as

$$(T_c - T_s)/g_0 h = \zeta + \Xi(0, \tau)\ Z(\zeta, \tau)$$

DISCUSSION

The values of a, h, and χ used in computing the graphs in Figs 2 to 5 were chosen to simulate the properties of a naturally occurring intrusion. From Figs 2 and 3 it is seen that in this example the surface thermal gradient may continue to be abnormally large ($g_s/g_0 > 1{\cdot}2$, say) for a period of the order of thousands of years after the injection of the magma. Similar periods of time are required for the intrusion to cool until the pre-existing temperature distribution is regained; this cooling is noticeably rapid near the surface where the vertical com-

TABLE 1.—Values of $\Xi_d(\xi, \tau)$

ξ	0	0·01	0·02	0·05	0·10	0·20	0·30
τ							
0·001	2·000	1·000	0·000	0	0	0	0
0·003	1·964	1·000	0·018	—	—	—	—
0·005	1·685	0·995	0·157	—	—	—	—
0·007	1·369	0·957	0·313	0	—	—	—
0·010	1·041	0·843	0·446	0·005	—	—	—
0·015	0·719	0·657	0·483	0·055	0	—	—
0·020	0·553	0·521	0·435	0·123	0·001	—	—
0·030	0·380	0·359	0·331	0·186	0·024	0	—
0·050	0·225	0·223	0·216	0·176	0·083	0·004	0

TABLE 2.—Values of $\Xi_p(\xi, \tau)$

ξ	0	0·01	0·02	0·05	0·10	0·20	0·30
τ							
0·001	2·000	1·000	0	0	0	0	0
0·003	1·876	0·827	0·012	—	—	—	—
0·005	1·264	0·709	0·094	—	—	—	—
0·007	0·799	0·540	0·162	0	—	—	—
0·010	0·442	0·355	0·183	0·002	—	—	—
0·015	0·210	0·189	0·138	0·015	—	—	—
0·020	0·122	0·115	0·095	0·027	0	—	—
0·030	0·055	0·054	0·050	0·028	0·004	0	—
0·050	0·020	0·020	0·019	0·016	0·007	0·001	0

TABLE 3.—Values of $Z(\zeta, \tau)$ and $Z'(0, \tau)$

	$Z(\zeta, \tau)$									$Z'(0, \tau)$
ζ	0·01	0·02	0·05	0·10	0·15	0·20	0·40	0·60	0·80	
τ										
0·001	0·489	0·490	0·475	0·450	0·425	0·400	0·300	0·200	0·100	281·6
0·003	0·485	0·490	—	—	—	—	—	—	—	93·55
0·005	0·417	0·488	—	—	—	—	—	—	—	55·89
0·007	0·339	0·469	—	—	—	—	—	—	—	39·78
0·010	0·255	0·412	0·475	—	—	—	—	—	—	27·71
0·015	0·176	0·318	0·470	—	—	—	—	—	—	18·31
0·020	0·132	0·250	0·437	0·450	—	—	—	—	—	13·80
0·030	0·088	0·171	0·356	0·441	0·425	0·400	—	—	—	8·90
0·050	0·051	0·101	0·235	0·371	0·408	0·398	0·300	0·200	0·100	5·14

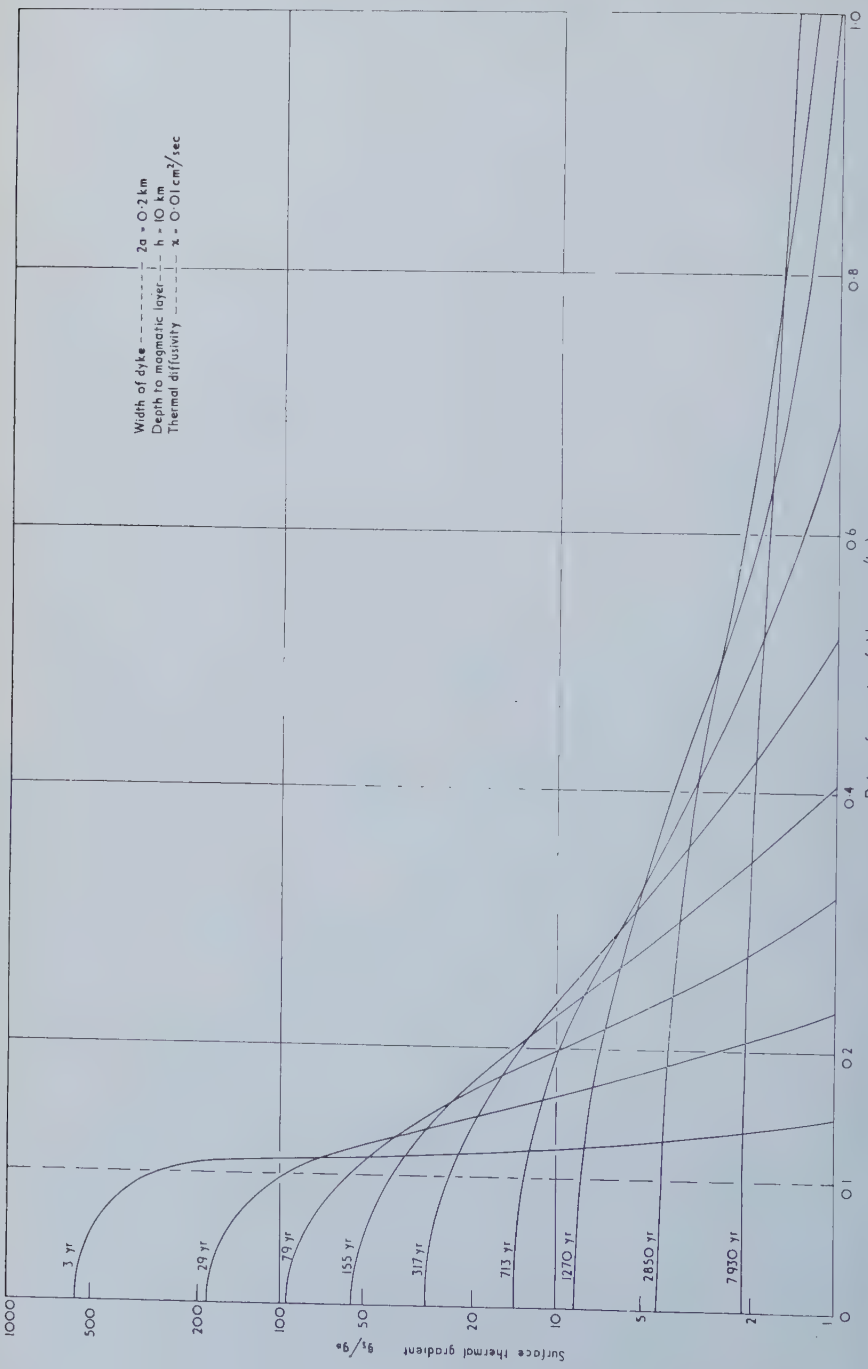

FIG. 2.—Surface thermal gradient due to a cooling dyke.

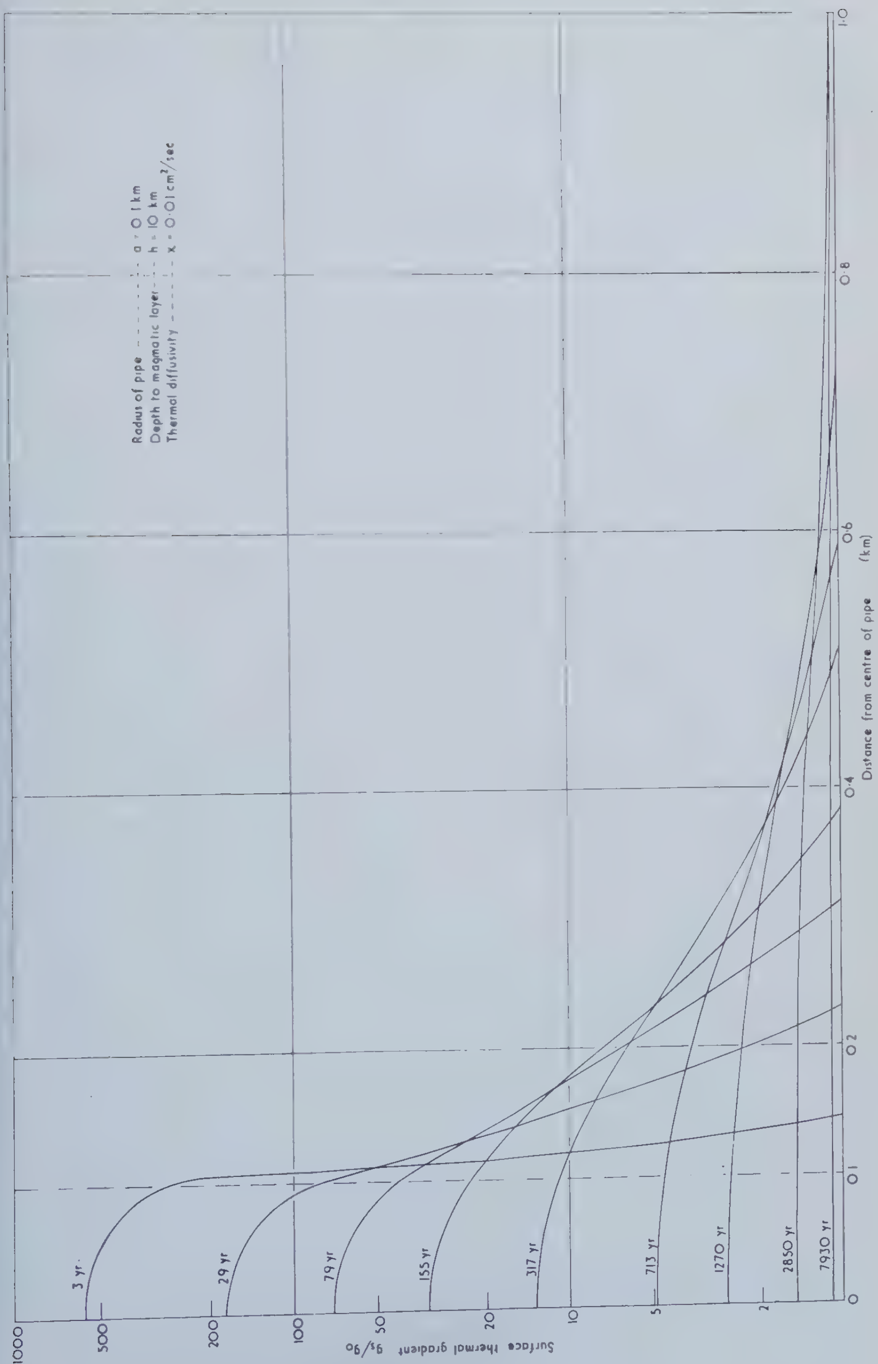

FIG. 3.—Surface thermal gradient due to a cooling pipe.

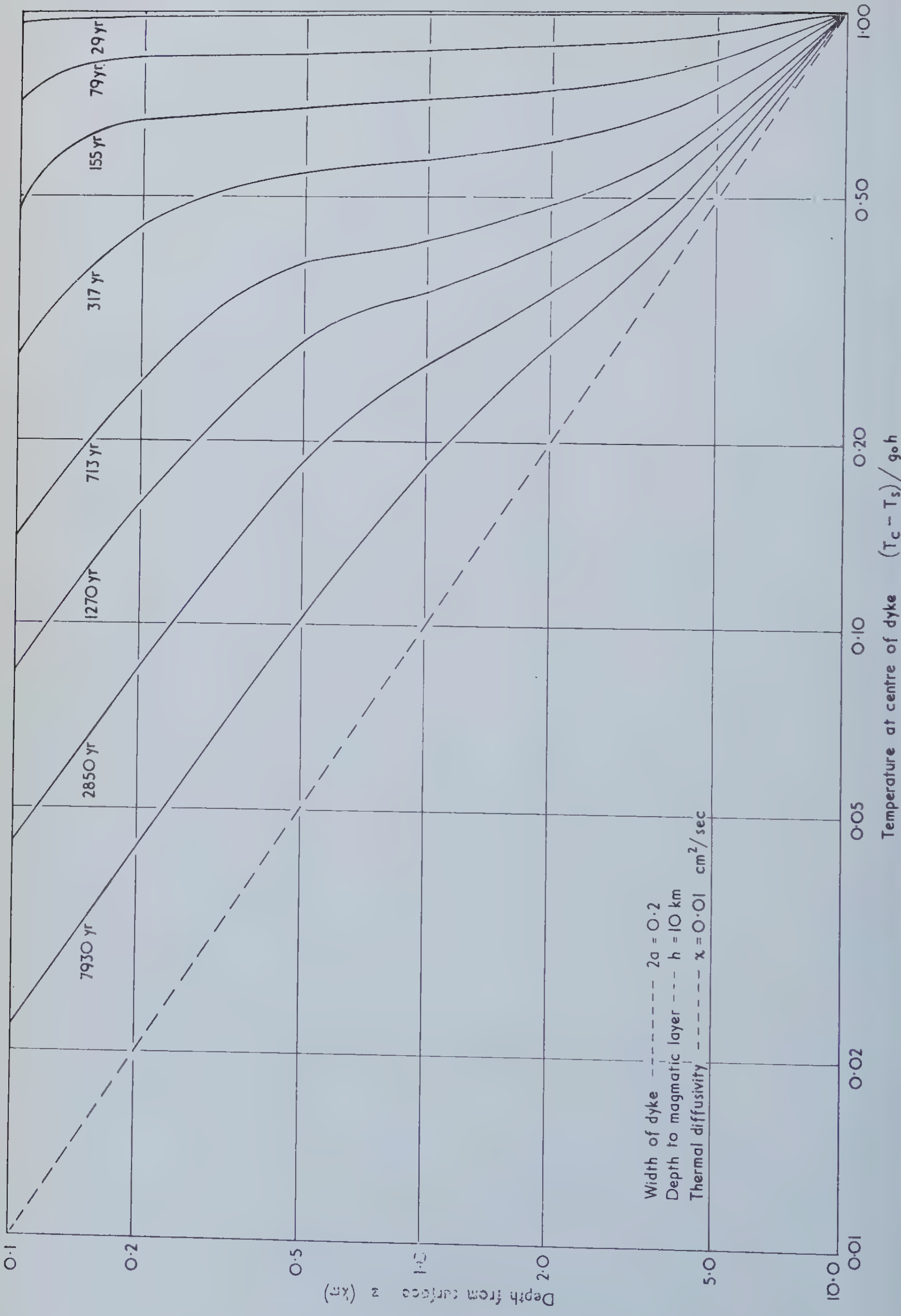

FIG. 4.—Temperature at the centre of a cooling dyke.

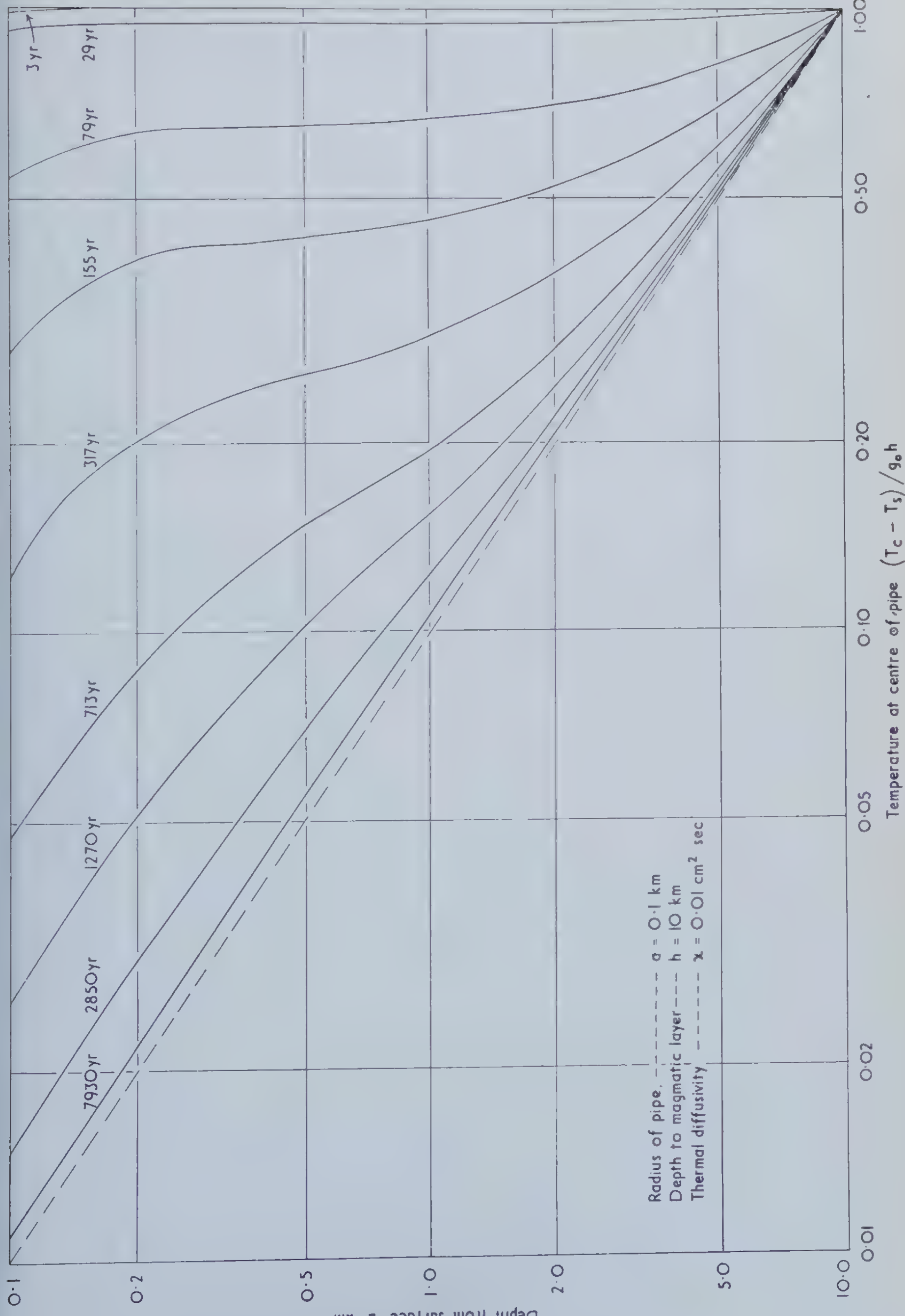

FIG. 5.—Temperature at the centre of a cooling pipe.

ponent of heat flow is important, and slower at depth, where the horizontal component of flow predominates. Under actual conditions, cooling would on the one hand be retarded by the release of the latent heat of fusion of the magma, and on the other accelerated by the convective transfer of heat to the surface by ascending water.

ACKNOWLEDGEMENTS

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UPPER JURASSIC FOSSILS AND HYDROCARBON TRACES FROM THE CHEVIOT HILLS, NORTH CANTERBURY

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Summary

Upper Jurassic fossils (*Buchia* aff. *malayomaorica*, *B.* aff. *subpallasi*, *Inoceramus* spp. *Anapaea* sp., and *Hibolithes brownei*) are recorded from the Cheviot Hills. The fossiliferous rocks emit an oily smell when freshly crushed, and contain very small quantities of hydrocarbon, mostly methane.

Introduction

In his "Divisions and Faunas of the Hokonui System (Triassic and Jurassic)", Marwick (1953) recorded a single Jurassic fossil from North Canterbury—the ammonite *Dalmasiceras speighti* Marshall from Ethelton, which Arkell (1953) subsequently classed as *Idoceras* (Lower Kimeridgian). Previously (in Fyfe, 1934 : 4) Marwick had identified *Buchia* from the coast south of Waiau River, but he later reported these fossils as Cretaceous *Aucellina* (Finlay and Marwick, 1948 : 17). In this paper, Upper Jurassic fossils are identified from several localities in the hills between Cheviot and the coast, some 15 miles north-east of Ethelton.

Fossil Localities

In 1882 Alexander McKay visited Motunau to examine a deposit of moa bones exposed by a flood, and then proceeded to Cheviot to collect fossils from Tertiary and "Cretaceo-tertiary" strata. He reported (McKay, 1883 : 79) collecting fragmentary saurian bones from the western slopes of the coast range between Gore Bay and the Waiau-ua River, where saurian beds rest on "Triassic rocks".

McKay's collection GS 502 (S62/529) from "Coast Range (west slope), Cheviot Hills Station to Waiau-ua River, 1882" (Hector, 1887 : 265) is preserved at the Geological Survey. It contains two types of material. Five pieces of siliceous fine sandstone, containing poorly preserved bone fragments and Mollusca of Piripauan–Haumurian age, can be attributed to the Upper Cretaceous saurian beds or "boulder sands" of the covering strata. The other specimens, however, probably parts of a single boulder, are pieces of fine-grained dark limestone containing abundant well-preserved shells of an Upper Jurassic *Buchia* (described below) and must be considered part of the basement Hoko-

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nui rocks, classed as Triassic by McKay, that unconformably underlie the Upper Cretaceous and Tertiary covering strata. Probably the boulder found by McKay came directly from the undermass, and not from an Upper Cretaceous conglomerate; a limestone boulder could not have survived the leaching that preceded deposition of Upper Cretaceous sediments.

Other Upper Jurassic fossils were discovered in the Cheviot Hills by Dr J. Marwick and Mr H. E. Fyfe during the geological survey of Amuri-Kaikoura Subdivision in 1933-34.

GS 3429, 110 chains west of Trig Sub. K, Woolshed Stream, about ¼ mile south-east of Glenkens Station, is a stream-worn alveolar fragment of a canaliculate belemnite guard (S62/530, grid ref. 618429).

GS 3441, 45 chains east-south-east of Trig Sub. E (Mt Beautiful), drift at creek mouth (S62/532, grid ref. 671442), and GS 3446, 48 chains east of Trig Sub. E, 5 chains from coast, 1¼ miles south of Waiau River mouth (S62/531, grid ref. 671445) are fossiliferous boulders of sandstone and dark mudstone derived from the badly slumped seaward slope of the Cheviot coast range, containing abundant crushed shells of *Buchia* and fragments of members of the Inoceramatidae. The localities are about 15 chains apart and the boulders probably came from the same bed.

In August 1957, Mr J. D. Campbell, of Canterbury University, examined the area from which Mr Fyfe's collections were made. He confirmed the presence of fossiliferous concretions in mudstone on the coast south of Waiau River and traced them westward south of Mt Beautiful, and obtained abundant *Buchia* aff. *malayomaorica* Krumb. and *Inoceramus* spp. His collections (S62/524-526) were collected *in situ* from the probable source beds of GS 3441 and 3446, at points between Mt Beautiful and the coast.

Mr Campbell also searched Woolshed Stream and discovered a concretionary boulder containing *Buchia* aff. *subpallasi* (Krumb.) (S62/528, grid ref. 620430).

GEOLOGY

The name Cheviot Hills is applied to a ridge of Hokonui rocks culminating in Mt Maccoinnich (1,100 ft), Mt Caverhill (1,345 ft), and Mt Eleanor (1,181 ft), extending from the Jed River to the Waiau River, bounded on the east by the coast and on the west by the Cheviot depression (Fyfe, 1933 : 6). The ridge is the southern end of the core of a south-westward plunging Tertiary anticline, the Hawkeswood Block of Fyfe (1934 : 4), defined by Upper Cretaceous and Tertiary covering strata that wrap around its nose in the south and lap on its western flank (Fig. 1).

The structure of the older Mesozoic rocks of the anticline has not been determined. They are steeply dipping or vertical, and strike WSW

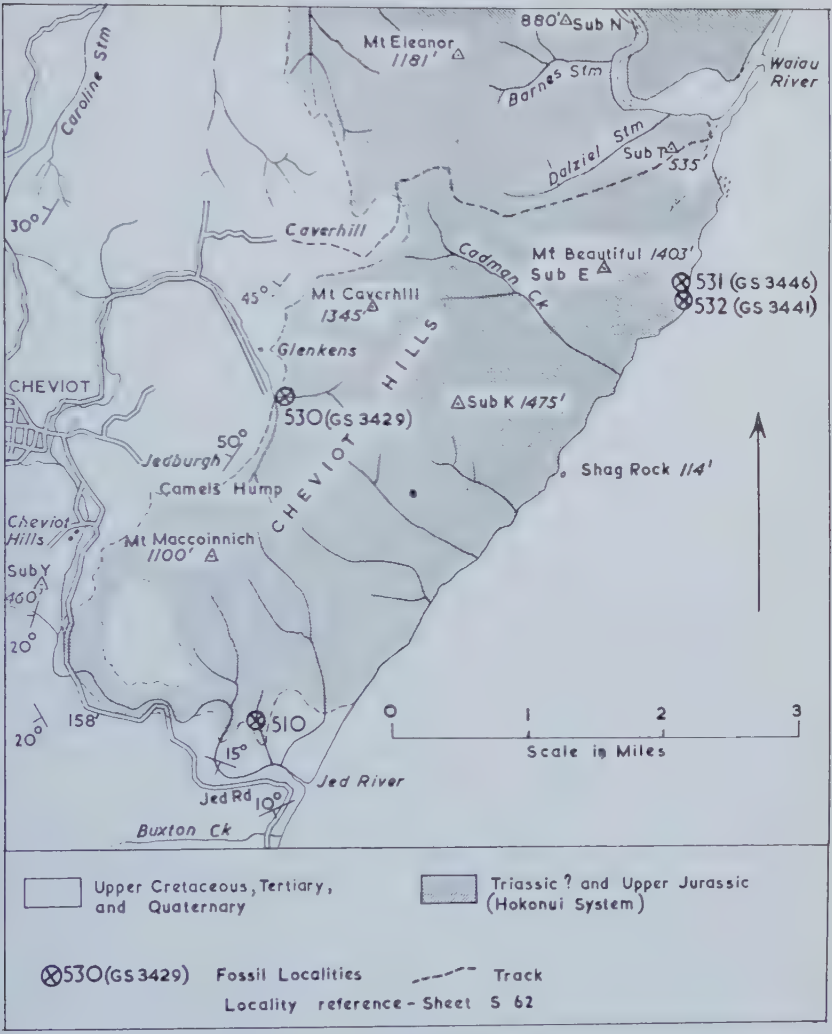

FIG. 1.—Geological sketch-map of Cheviot Hills, North Canterbury, to show Lower Mesozoic fossil localities. Part of NZMS 1, sheet S 62. Geology after H. E. Fyfe, New Zealand Geological Survey, 1934, simplified.

near Mt Beautiful. In the south, towards Jed River, fossils (S62/510, grid ref. 614387) have been found by Mr J. D. Campbell (pers. comm.) in marble associated with pillow lava mentioned by Fyfe (1934 : 4), similar to occurrences of Norian (Upper Triassic) fossils elsewhere in Canterbury, but not determinable. Pillow lava, epidotised basic igneous rock, cherty red siltstone, and jaspillite, associated with sheared and brecciated greywacke and argillite, were mapped by Mr Fyfe at intervals up the coast and inland as far north as Mt Beautiful. Locally, on both flanks, he mapped the notable igneous conglomerate which had been recognized elsewhere to contain "pebbles of pillow lava amongst the numerous plutonic, volcanic, and greywacke pebbles, a fact indicating a break in the greywacke rocks" (Fyfe, 1933 : 6).

As a result of his recent field work, Mr J. D. Campbell believes that the coastal sequence is simple, that the fossiliferous beds are interbedded with a typical North Canterbury greywacke series and have spilites both above and below them. Undoubtedly, knowledge of the fossils, age, and structure of the Cheviot Hills will increase with further field work.

PALEONTOLOGY

Class PELECYPODA

Family PTERIIDAE

Buchia aff. **malayomaorica** (Krumbeck). Figs 6 to 9

1934 *Buchia;* Marwick in Fyfe, N.Z. geol. Surv. 28th annu. Rep. (n.s.) : 4.

1948 *Aucellina;* Finlay and Marwick, Outline N.Z. Geol. : 17.

Compare:

1923 *Aucella malayomaorica* Krumbeck, Paläont. Timor 12 (12) : 65, pl. 173, figs 2-12, 17; pl. 177, fig. 13.

1926 *Aucella boehmi* Marwick, Trans. N.Z. Inst. 56 : 305.

1936 *Aucella* sp., ? aus der Gruppe der *A. malayomaorica;* Wandel, Neues Jb. Min. Geol. Paläont. Beil.-Bd. 75B; 461, figs 1a-c.

1940 *Buchia malayomaorica* (Krumb.); Teichert, J. roy. Soc. W. Aust. 26 : 109.

1945 *Buchia malayomaorica* (Krumb.); Glaessner, Proc. roy. Soc. Vict. 56 (2) : 154 (synonymy).

In boulders derived from the coast range in the vicinity of Trig Sub. E (Mt Beautiful) and in Mr Campbell's collections from outcrops in the same area, crushed *Buchia* occur in large numbers, closely packed in a matrix of fine dark mudstone and sandstone, a facies characteristic of *B. malayomaorica* in the East Indies and in the Kawhia district of New Zealand. Figures 7 and 8 illustrate a relatively uncrushed left valve (GS 3446), showing the characteristic roundly oval shape, low beak, arched hinge line, excavated behind and below the beak, strengthened irregularly in the byssal area in the front of the beak, and the irregular sculpture of concentric lamellae, crossed by radial threads well developed on some specimens, obsolete on others. Right valves (Figs 6, 9) have a stout byssal ear and a strong ligamental ridge on the hinge plate, rising above the true dorsal shell margin.

Specimens from GS 3441 and 3446 have been compared with the form recorded as *Aucellina* from the Taitai Series of Koranga (Marwick, 1939) to which Finlay and Marwick (1948) considered they were related. The Koranga species, characterized by its extremely high, wide, swollen, and incurved left-valve beak, and by dominantly radial sculpture, is amply distinct from the low-beaked left valves from GS 3441 and 3446.

The Canterbury specimens agree with *B. malayomaorica* in their crowded habit, shape, beaks, and sculpture, and right valves also agree in their stout, short ears, with a dorsal ligament groove running back past the umbo, separating the posterior dorsal shell margin from a high nymph-like ridge that rises above the beak. The right valves differ from New Zealand specimens of *B. malayomaorica* chiefly in the closer approximation of ear to the protruding anterior margin, which reduces the byssal notch to a narrow slit. This difference between right valves of *B.* aff. *malayomaorica* from Cheviot Hills and those of "*B. boehmi* Marwick" from Kawhia is fairly constant in the available series, but its significance is uncertain. Krumbeck's type series of *B. malayomaorica* from Timor includes right valves with both widely open notch (e.g. pl. 173, fig. 8; pl. 177, fig. 13) and narrow notch (pl. 173, fig. 3), the latter resembling the Cheviot specimens. Wandel's specimens from Buton (1936, pl. 17, fig. 1) and East Celebes (pl. 17, fig. 4, 11) agree with *B. boehmi* in their wide gaping notch, and he separated as "*Aucella* sp.?, aus der Gruppe der *A. malayomaorica*" specimens from the Demu Limestone and Lilinta Marly Limestone of Misol including a right valve with narrow byssal notch and straight hinge-line approaching the condition in *Aucellina* (cf. Pompeckj, 1901, pl. 16). These aberrant specimens from the Demu limestone and Lilinta beds are *older* than typical *B. malayomaorica* (with *Inoceramus haasti*) recorded by Wandel (1936 : 514) from Misol. Although they agree with the Cheviot Hills specimens in their narrow byssal notch, they disagree in their strong radial sculpture and straight hinge-line.

Buchia malayomaorica (Krumbeck) has been widely cited as upper Lower Oxfordian in the East Indies (Krumbeck, 1923), but at Kawhia, New Zealand, it first appears in the Heterian Stage at a slightly higher horizon than the Lower Kimeridgian ammonites identified by Arkell (1956 : 455) and ranges up into the Ohauan (approximately middle Kimeridgian by later ammonite determinations). It is replaced by *B.* aff. *extensa* (Holdhaus) and *B. plicata* (Zittel) in the lower part of the Puaroan Stage, but its lineage reappears in the Puti Point beds on the north shore of Kawhia (containing ammonites probably of Lower Tithonian age; Spath, 1923). Recent field work has shown that the Puti Point beds overlie the Puaroan conglomerates, and are thus best treated as an upper part of the Puaroan. The representative of *B. malayomaorica* in the Puti Point beds is consistently different from its predecessors, and is perhaps closer to the East Indies form *B. misolica* (Krumbeck, 1934 : 454) in its well developed fine radial and lamellate concentric sculpture. Like the Canterbury shells, it has a narrower byssal notch than most *malayomaorica*.

The occurrence at Kawhia of representatives of *Buchia malayomaorica* (usually considered an "archaic" species in the evolution of the genus) both below and above the horizon of the more advanced species *Buchia plicata* (Zittel) helps to reconcile the different interpretations of *Buchia* sequence in New Zealand (Marwick, 1926), Western Australia (Teichert, 1940; Brunnschweiler, 1951) and the East Indies (Krumbeck, 1934). Two parallel lineages, one represented by *malayomaorica* and *misolica*, the other by the *plicata-subpallasi* group, lived in the south-east Tethyan region during the Kimeridgian-Tithonian. Although *B. malayomaorica* has often been cited as an Oxfordian fossil, the writer knowns of no occurrence where its Oxfordian age has been firmly established by ammonite determinations.

The poorly preserved Canterbury shells can be definitely attributed to the group of *B. malayomaorica* which is known to range from Lower Kimeridgian to Lower Tithonian in New Zealand, but as they differ from Kawhia specimens, they may be somewhat different in age.

Buchia aff. ***subpallasi*** (Krumbeck). Figs 2 to 5, 16

1921 *Aucella* sp.; Henderson, N.Z. J. Sci. Tech. 4 : 27.

1934 *Aucella subpallasi* Krumbeck, Neues Jb. Min. Geol. Paläont. Beil. Bd. 71B : 450-454, pl. 15, fig. 11; pl: 16, figs 1-10.

1940 *Buchia subpallasi* (Krumbeck); Teichert, J. roy. Soc. W. Aust. 26 : 103-118, pl. 1, figs 8-12.

This distinctive species of *Buchia*, not previously recorded from New Zealand, is known from the following localities:

GS 502 (S62/529), boulder of black limestone, western slopes of Cheviot Hills between Cheviot Hills Station and Waiau River, coll. A. McKay, 1882.

S62/528, boulder of concretionary mudstone, Woolshed Stream, south-east of Glenkens Station, Cheviot, coll. J. D. Campbell, 1957. This locality falls within the area of McKay's collection but the fossils are preserved in different matrix.

GS 5828 (S41/531), undermass in Gore River, Clarence Valley, Marlborough, associated with *Inoceramus* sp., *Anopaea* aff. *verbeeki* Boehm, and *Buchia* ? aff. *malayomaorica* (Krumb.), coll. G. W. Grindley and D. R. McQueen, February, 1953.

The Gore River collection will be described elsewhere, but figures of *Buchia* aff. *subpallasi* are given here for comparison with examples from Cheviot Hills.

The New Zealand specimens, very consistent in shape, torsion of shell, and prominence of beak, clearly belong to a uniform population. They resemble specimens from the Northern Hemisphere (Alaska, Canada, Greenland, Spitzbergen, Russia, etc.) usually classed as members of the group of *B. mosquensis* (von Buch) (including its synonym, *B. pallasi* (Keyserling), *fide* Pavlov, 1907 : 22), but are still more like fossils from the island of Misol in the East Indies, and from Western Australia, described under the name of *Buchia subpallasi* (Krumbeck). The following comparisons are with specimens selected for their close resemblance to the New Zealand form.

Among the many "species" of *Buchia* (*Aucella*) from Russia figured by Pavlov (1907), the shells with the most resemblance to the Marlborough and Canterbury form are Portlandian. Pavlov's lectotype of *Avicula mosquenis* von Buch (Pavlov, 1907, pl. 2, fig. 5a-c) differs from the New Zealand form in its much less prominent beaks, lesser curvature of the shell axis, and its fairly well developed posterior wing (ear). According to Imlay (1955 : 86), however, specimens from near Moscow and Vetlanka Creek in Drenburg Province have as prominent umbos and as tightly coiled beaks as the figured specimens of *B. subpallasi* Krumb. Probably Pavlov (who drew narrower specific limits than modern writers) classed such specimens in different species (e.g. *gracilis, russiensis, fischeri*), but none of those he figured has such swollen umbos and coiled beaks as the New Zealand specimens, indicating their rarity, if not absence, from Russian populations.

Some of the species figured by Sokolov (1908) approach the New Zealand form more closely. Thus, the lower Sequanian specimen from Orenburg (South Urals), figured as *A. bronni* var. *leguminosa* (Sokolov, 1908, pl. 1, fig. 4; *non* Stoliczka) has a curved axial line, obsolete posterior ear, and well developed beak, although its classification as a variety of *bronni* suggests that it is much less inflated, and has coarser radial sculpture than the *mosquensis* group. *A. lindstroemi* Sok. (Lower Sequanian) is as high (but narrow) in the beak, and *A. tschernyschewi* Sok. (Kimeridgian-Sequanian) from Timan, northern U.S.S.R., is as swollen as the New Zealand specimens, but the combination of characters is not matched in the specimens figured.

From Danmarks Havn, Greenland, Ravn (1911, pl. 32, fig. 7), figured as *A. tenuistriata* Lahusen a poorly preserved specimen with high arched beak, strongly curved axial plane, and obsolete posterior wing (resembling the New Zealand specimens) from boulders attributed to Lower Portlandian from the known range of Russian forms. The specimens from the Upper Kimeridgian and Lower Portlandian of Cape Leslie, East Greenland, figured by Spath (1936, pl. 42, fig. 1a-g) as *Buchia mosquensis* von Buch, do not include any with beaks as swollen and arched and axial line as curved as the New Zealand form. Similarly, Alaskan specimens of *B. mosquensis* (Imlay, 1955, pl. 9, fig. 17-19), dated as Middle Kimeridgian, while agreeing in general form with the New Zealand specimens, lack their extreme high beaks and curved growth form.

In the upper Jurassic of the west coast of Vancouver Island, British Colombia, Jeletzky (1950) has recorded a sequence of *Buchia* populations in beds dated as Oxfordian to Portlandian. Dr Jeletzky has kindly forwarded to the writer a series of casts and specimens which include two individuals approaching the New Zealand population here discussed. One (G.S. Can. 18992/2) identified as "*Aucella* ex. gr. *mosquensis* (von Buch) approaching *subpallasi* Krumbeck" differs in its blunter (lower and broader) beak, the other (18992/1) identified as transitional between *mosquensis, russiensis* (Pavlov) and *mniovnikensis* (Pavl.) has narrower beaks but lacks the pronounced torsional growth of the Cheviot-Gore River shells. These Canadian specimens are from beds classed in Jeletzky's Division B. of the Portlandian in the broad sense, perhaps Lower Portlandian.

Of the many forms of *Buchia* recorded by Anderson (1945) from the Knoxville Series of California (equivalent to the middle Tithonian of Mexico, *fide* Arkell, 1956 : 553) none combines the characters of the New Zealand shells, but *B. elderensis* (Anderson) is almost equally curved and *B. andersoni* approaches them in beak characters. The writer has seen no illustrations of the *Buchia* recorded by Burckhardt (1906, 1912) from Mexico, where members of the *mosquensis* (= *pallasi*) group are reported as early as Middle or even Lower Kimeridgian (Spath, 1936 : 167).

Imlay (1955 : 85) has suggested that *Buchia mosquensis* (von Buch), so widely distributed in the north temperate region, may be represented in India by *B. blanfordiana* (Stoliczka) but the latter is a consistently larger and more inflated form with coarser concentric ribbing, very rarely showing any radial sculpture, closely related to *B. plicata* (Zittel). *B. blanfordiana* and *B. plicata* may be related to the *B. mosquensis* group through the more coarsely sculptured (but radially striated) group now usually called *B. rugosa* (Fischer) (= *Aucella pallasi* var. *plicata* Lahusen, 1888, not of Zittel) but they obviously represent a different species from the small, neat, radially sculptured group that includes *mosquensis* and *subpallasi*.

Imlay also suggested (p. 85-6) that *Buchia subpallasi* Krumbeck, from the upper Jurassic of Misol, is doubtfully distinct from *B. mosquensis* (von Buch). Although *B. subpallasi* almost certainly represents the stock of *mosquensis* in the East Indies area, the specimens illustrated by Krumbeck are consistent in their broad arched beaks and subdued posterior wing and differ from at least the majority of northern *mosquensis* in such a way as to suggest that they are a population intermediate in morphology, as they are in space, between *mosquensis* and the New Zealand shell here figured, which is still a more extreme form, with higher and narrower more incurved beaks, more narrowly arched high line, and greater curvature of axial line.

B. subpallasi was described from the "Aucella sandstone" of the island of Misol (Indonesia) at the base of the Lilinta Beds, overlying the Lias and overlain in succession by higher formations of the Lilinta beds (Demu Limestone, Fatjet shales) and then by the Fatjet Limestone, part of which is Neocomian. The correlation of this section has never been certain and its base is variously placed as Oxfordian to

Kimeridgian (van Bemmelen, 1949). Krumbeck (1934 : 429) concluded that the "Aucella sandstone" could not be certainly dated in the absence of ammonites, but placed it in the Kimeridgian, although a younger age was not excluded. Stolley (1929) correlated the Lilinta Beds with the Oxfordian on the basis of their belemnites, which, however, closely resemble species dated by associated ammonites as Kimeridgian and Lower Tithonian in New Zealand. Stolley's correlation by belemnites is therefore rejected, and the "Aucella sandstone" of Misol is considered Kimeridgian or younger, a conclusion more in keeping with the *Buchia* succession in the Himalaya and in New Zealand (see Teichert, 1940 : 110).

From the above summary it appears that the *Buchia* population sampled in the Cheviot Hills and Gore River is a specialized member of the group of *B. mosquensis* (von Buch), a species ranging in Northern Europe from the uppermost zone of the middle Kimeridgian to the lowest zone of the Portlandian (Spath, 1936 : 166-7), a range corresponding approximately to the Lower Tithonian, and that the forms most like the New Zealand specimens are Lower Portlandian (Vancouver), Middle Tithonian (California), or Upper Jurassic of uncertain stage, probably Kimeridgian or Tithonian (Misol).

The absence of *Buchia* aff. *subpallasi* (and its companions *Inoceramus* sp., *Anopaea* sp.) from the upper Jurassic rocks of western Auckland, which contain abundant *Buchia* and *Inoceramus* of other species, suggests that their age may fall outside the limits of the Auckland sections. The sequence of *Buchia* and *Inoceramus* zones, their correlation by associated ammonites (Arkell, 1956; Spath, 1923) is as follows:

	N.Z. Stage	*Buchia*	*Inoceramus*
Lower Tithonian	Puaroan	*B.* aff. *misolica* (Krumb.) *B. plicata* (Zitt.) *B.* aff. *extensa* (Holdh.)	*Inoceramus* n.sp. (Puti) *I.* aff. *everesti* Oppel *I.* aff. *everesti* Oppel
Middle Kimeridgian	Ohauan	*B. malayomaorica* (Krumb.)	*I. haasti* Hochst.
Lower Kimeridgian	Heterian	*B. malayomaorica* (Krumb.) (no *Buchia*)	*I.* aff. *galoi* Boehm *I. galoi* Boehm
? Bathonian	Temaikan	(no *Buchia*)	*I. inconditus* Marw.

From its overseas relationship, *B.* aff. *subpallasi* is unlikely to be pre-Heterian but could well be as young as Lower Portlandian and thus younger than the Lower Tithonian Puaroan Stage, most (if not all) of which seems to correspond with the lowest Tithonian zone (Contiguus Zone of Spath). An Upper Puaroan or post-Puaroan age is supported by the occurrence of *B.* aff. *misolica* Krumbeck in the Upper Puaroan, since this form is associated with *B. subpallasi* in Misol.

Family INOCERAMATIDAE

Inoceramus n.sp. A, ?aff. ***everesti*** Oppel. Fig. 12

Compare:

1913 *Inoceramus everesti* Oppel; Holdhaus, Palaeont. indica (ser. 15) 4 (2) : 415, pl. 98, figs 12-14.

The Inoceramatids collected by Mr J. D. Campbell from the coastal area south of Waiau River include three types distinguished by shape and sculpture, none of which can be classed in any of the five species recorded from the New Zealand Jurassic (Marwick, 1953 : 92-3). One form, represented by an incomplete double-valved specimen (Fig. 12), and by several incomplete valves, is moderately inflated, with the anterior margin set at about 90° to the hinge-line, and bears fairly regular close concentric ribs, perhaps more distinct on the internal mould than on the exterior surface of the shell. The only similar species from the Tethyan region noted in available literature are *Inoceramus everesti* Oppel from the Spiti Shales, and *I.* aff. *everesti* (Marwick, 1953, pl. 12, fig. 4) from the *Buchia* aff. *extensa* zone of the Puaroan Stage of Waikato Heads (classed as Ohauan by Marwick).

The specimen here figured differs from *I. everesti* in its greater inflation, less-developed posterior wing, closer spaced concentric ridges, which have a greater radius of curvature. It also differs from *I.* aff. *everesti* Marwick in inflation and in curvature of ridges. It is possibly an extremely narrow form of *Anopaca n.sp.* described below.

LOCALITY. Boulders derived from localities S62/526 and S62/523.

Inoceramus n.sp. B, ?aff. ***gracilis*** Holdhaus. Fig. 13

Compare:

1913 *Inoceramus gracilis* Holdhaus, Palaeont. indica (ser. 15) 4 (2) : 417, pl. 98, figs 15a-c.

A single right valve internal mould S62/525-26 differs markedly from its companions in its narrow beak, mytiloid shape, relatively great convexity, and weak sculpture, consisting of faint low somewhat irregular and distant folds on the cast, contrasting strongly with the strong sculpture of *I.* n.sp. A. This specimen is probably conspecific with three *Inoceramus* specimens from Gore River, Marlborough (GS 5828), and may be related to an unrecorded species from the Puti Point beds (upper Puaroan) of Kawhia (GS 6480). It differs from *I. gracilis* Holdhaus (described from a single specimen from Niti Pass, Himalaya) in its weaker sculpture, more oval outline and lower cross-section.

In a survey of the available literature on Jurassic *Inoceramus* from the Pacific and Tethyan regions, no Upper Jurassic forms closer to the Cheviot Hills specimens than the Spiti species cited have been noted. The Cheviot specimens differ strongly from the well-known *galoi-subhaasti-haasti* sequence, dated as Oxfordian in Misol, but Kimeridgian in south-west Auckland, New Zealand, and are in some respects more like the weaker-sculptured Middle Jurassic forms (*I. inconditus* and *I. brownei*).

Genus ***Anopaea*** Eichwald

1861 Soc. Nat. Moscou Bull. 34 (3) : 301.
1865 Lethaea Rossica 2 : 479.

Type Species (by monotypy): *Inoceramus lobatus* Auerbach & Frears, 1846 (not of Münster, 1836) = *I. bilobus* "Auerbach", Trautschold, 1858 (not seen). "Neocomian", Russia.

The following diagnosis is from Tryon (1884 : 278):

"Equivalve, inequilateral, elongated, with the shorter anterior part narrower, beaks close together, with a deep circumscribed lunule in front of them; ligament situated in a number of roundish pits in the straight cardinal margin, which has a rib-like tooth in the left valve below the beak, extending anteriorly for a short distance. Principally differs from *Inoceramus* by the presence of a deep lunule and by the internal hinge-rib (in the left valve)."

Anopaea n.sp. Figs 14, 15

Shell of moderate to large size, rather flat, oval in shape, with small pointed beak projecting above the hinge line near its central point, directed weakly forwards and inwards. Anterior dorsal margin of right valve continuing line of posterior dorsal margin in a gentle curve, not set at an acute angle as in most *Inoceramus*. Anterior margin of left valve descending more steeply and excavated to form a byssal sinus. Similar asymmetry, with a deeply excavated byssal sinus (termed "lunula" by Boehm) in the left valve, is shown in Boehm's figure (1904, fig. 4a) of *A. verbeeki* from Taliabu, East Indies and by the figures of the type species (Auerbach & Frears, 1846, pl. 7, fig. 2) and of *A. cuneiformis* (d'Orbigny) (1845, pl. 41, fig. 11, 12) from Russia. Sculpture of irregularly spaced low rounded folds, strongest on the disc, obsolete on the flanks, especially behind, and on adult shell, more distinct on internal mould than on exterior, rarely branching, superposed on irregular major undulations giving a gently stepped profile. No radial sculpture visible. Shell structure prismatic. Ligament not seen.

Estimated length (largest specimen): 120 mm.

LOCALITY. Boulders derived from localities S62/526 and S62/525.

REMARKS. Although this is the first published identification of the genus from New Zealand, specimens identified as *Anopaea* aff. *verbeeki*

Boehm, from Gore River (GS 5828), have been in the Geological Survey Collections for several years. The Cheviot Hills specimens differ from *A. verbeeki* in their lesser inflation, smaller size, and lack of radials, but are apparently congeneric. *A. windhouweri* Boehm differs in shape and in its coarser concentric sculpture. Both these species are from the "Grenzschichten" of Taliabu, Sula Islands, correlated with the upper Tithonian Lochambel Beds of the upper Spiti Shales.

Other species of *Anopaca* include the type species ("ferrugineous Neocomian" of Kotelniki and Wytkrino, Moscow), *A. attenuata* Eichwald, 1865 (Neocomian, Kotelniki), and *A. cuneiformis* (d'Orbigny) 1845 (Khoroschowo, Moscow: Upper Jurassic *fide* d'Orbigny: Upper Neocomian, *fide* Eichwald); and *A.* (?) *strambergensis* G. Boehm (Stramberg Limestone of northern Carpathians, Upper Tithonian). Judged by its shape *Inoceramus stoliczkai* Holdhaus (1913, pl. 98, fig. 10, 11) from the Middle Spiti Shales (about Lower Tithonian) is related to *Anopaca windhouweri* Boehm and the Cheviot Hills specimens, and may be an *Anopaca*. Possibly the three Russian species are Tithonian, not Neocomian, since Eichwald classed as Neocomian certain beds later found to be Upper Jurassic (Pavlov, 1901 : 6). Gillet (1924-1925) did not list *Anopaca* in her survey of Neocomian lamellibranchs.

Class CEPHALOPODA

Family BELEMNOPSIDAE

Hibolithes brownei (Marshall), emend. Marwick. Figs 10, 11

1909 *Orthoceras brownei* Marshall, Trans. N.Z. Inst. 41 : 44, pl. 14A.
1953 *Belemnopsis brownei* (Marsh.); Marwick, N.Z. geol. Surv. pal. Bull. 21 : 124, pl. 17, figs 3, 4, 9 (with synonymy).

The writer has transferred this species to the genus *Hibolithes*, owing to its close resemblance to East Indies species (*H. lagoicus* (Boehm), *H. G. boehmi* Stolley, and *H. windhouweri* Stolley) classed as *Hibolites* by Stolley (1929). Montfort's original spelling (1808, p. 386-7) is *Hibolithes*.

Recent field work has shown that *Hibolithes brownei* (Marsh.) is the characteristic belemnite of the lowest zone in the siltstones of Puti Point, Kawhia, perhaps ranging down into the Waiharakeke Conglomerate, but unknown in older and younger beds in the Kawhia section. It has not previously been identified in other parts of New Zealand, so its recognition in the Cheviot Hills is of considerable interest. The specimen (GS 3429, Woolshed Creek, $\frac{1}{4}$ mile SE of Glenkens Station) is a short length of guard in the alveolar region, enclosing the basal part of the phragmocone. Identification as *H. brownei* is based on the dimensions of the laterally compressed cross section and on the shallow narrow ventral groove, features that agree perfectly with abundant specimens of *H. brownei* but cannot be matched in any other New Zealand Jurassic Belemnopsidae known.

Hibolithes browenei (Marsh.) is apparently restricted to the basal zone of the upper part of the Puaroan Stage (Puti Point beds) of Kawhia, where it occurs with ammonites attributed to the Contiguus Zone (Lower Tithonian) by Spath (1923).

AGE OF CHEVIOT HILLS JURASSIC

Although few of the fossils were collected in place, their preservation suggests that they are from the indurated sediments forming the Cheviot Hills and not from boulders in younger conglomerates. They thus suggest that the rocks are at least in part Upper Jurassic. The evidence for more precise dating may be summarized:

Buchia aff. *subpallasi* (Krumbeck)—approximately Lower Tithonian.
Buchia aff. *malayomaorica* (Krumbeck)—(? Oxfordian), Kimeridgian-Tithonian.
Inoceramus n.sp. A. ? aff. *everesti* Oppel—? Tithonian.
Inoceramus n.sp. B. ? aff. *gracilis* Holdh.—? Tithonian.
Anopaea n.sp.—Tithonian (? Upper Tithonian).
Hibolithes browenei (Marshall)—Lower Tithonian.

CORRELATION WITHIN NEW ZEALAND—The pelecypod assemblage from Gore River, Marlborough, containing *Buchia* aff. *subpallasi*, *B.* aff. *malayomaorica*, *Inoceramus* cf. sp. B, and *Anopaea* is clearly similar to that of the Cheviot Hills.

The Puaroan Stage of south-west Auckland contains a similar *Buchia* aff. *malayomaorica*, *Inoceramus* aff. *everesti*, a species perhaps related to *I.* sp. B. *aff. gracilis*, and *Hibolithes browenei*, but the faunal resemblance is not close. The specimen of *H. browenei* is isolated and may indicate the presence of beds contemporary with the Puti Siltstone to which it is restricted at Kawhia. *B.* aff. *malayomaorica* belongs to a lineage now known to range through most of the Upper Jurassic, so cannot be used for close correlation. The remaining species differ from those of the Kawhia Upper Jurassic section (Heterian, Ohauan and Puaroan stages) and suggest that some sediments in the Cheviot Hills are younger than Puaroan.

CORRELATION OVERSEAS—The overseas affinities of *Buchia* aff. *subpallasi* and the association of *Hibolithes browenei* with *Aulacosphinctoides* and *Uhligites* at Kawhia point to Lower Tithonian age. *Anopaea* and the *Inoceramus* species from the east slopes of the Cheviot Hills seem closest to Tithonian (? Upper Tithonian) forms. *Buchia* aff. *malayomaorica* has not previously recorded so high in the Jurassic, but as a related form occurs in the Lower Tithonian at Kawhia; there is no reason to avoid classing all the fossils here described as Tithonian.

HYDROCARBON TRACES

"It seems to be accepted by every earlier investigator that all beds which were subject to the whole Hokonui Orogeny have reached a point of induration and incipient metamorphism which has destroyed any possibility of their retaining liquid hydrocarbons. We feel that this opinion should not be allowed to become an axiom as there seem to be definite exceptions to the rule."*

Several old reports of petroleum indications in the Cheviot area were listed by Morgan (1927 : 78). Henderson (1921 : 29-30) described kerosene odours in a crush zone in the "greywackes" 2 miles east of Cheviot and in a shatter zone three-quarters of a mile upstream from the mouth of the Jed, at each place close to the contact with overlying Upper Cretaceous covering sediments. Henderson considered that such oil in pug zones in the older rocks was possibly derived from younger rocks, but admitted that reports of similar traces near the coast north of Jed River are far from outcrops of younger sediments.

The fossiliferous *Buchia* limestone from the west slopes (GS 503) and several of the fossiliferous sandstone and mudstone boulders from the east side of the Cheviot Hills (GS 3441, 3446) emit a strong ephemeral kerosene-like odour when freshly broken or crushed.

A small specimen of GS 502 was submitted to the Dominion Analyst, who reported that only traces of soluble material were recovered when the pulverized sample was solvent-extracted, both before and after retorting.

A larger sample, a composite from GS 502, 3441, and 3446, was then submitted to the Dominion Analyst, who reported (23 September, 1957) that it was treated in the Gray King Assay apparatus of the Coal Section. The sample, ground to pass a 72 B.S. sieve, was heated *in vacuo* for 3½ hours, reaching a temperature of 700° C. The total loss was 0·9% of the original weight, made up of approximately 3 parts gas and 1 part water.

An analysis on the Haldane apparatus of part of the gas produced gave the following composition:

Carbon dioxide	46·5%
Oxygen	2·0%
Unsaturated hydrocarbons	present
Hydrogen	22·0%
Carbon monoxide	3·5%
Saturated hydrocarbons	1·5%
Nitrogen	24·5%

The unsaturated hydrocarbons could not be determined quantitatively, but their presence was proved by the brightening of a wire heated to only dull red heat.

The "n" value for the saturated hydrocarbons was slightly greater than 1·00.

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*E. Lehner and R. J. L. Stephens, 1951. Review of the Oil Prospects of New Zealand. D'Arcy Exploration Co. Ltd. Report on open file at New Zealand Geological Survey.

Portion of another part of the gas produced was examined on the Mass Spectrometer. The amount of hydrocarbons present was approximately 0·5%, and the report states "it is probable that half of the hydrocarbon content is due to methane. Other ions present are $C_2H_5^+$, $C_2H_3^+$, aand $C_2H_2^+$. There were several small peaks of 0·01 to 0·05% in the mass range 50 to 58, which suggest small quantities of hydrocarbons." Hence, saturated hydrocarbons, higher than methane, would appear to have been formed, to some extent, on heating this rock sample *in vacuo*.

As noted by Morgan (1925 : 287), the older sedimentary rocks of New Zealand (Paleozoic, Triassic, and Jurassic) are in general too altered and indurated to contain oil, except such as may have migrated from younger strata, and oil prospecting has generally been restricted to Cretaceous and Tertiary rocks. Traces of oil in crushed or jointed Mesozoic greywacke near Cheviot and near Ward, Marlborough, about 90 miles farther north, were therefore interpreted by Henderson (1921) and Morgan (1921) as the result of migration from younger rocks.

The widespread occurrence of kerosene odours and other traces in the Jurassic of the Cheviot Hills at considerable distance from younger rocks and the lack of such traces in the Tertiary covering strata of the same district make it unlikely that the hydrocarbons have migrated from younger rocks. The siltstones containing *Buchia* are lower in metamorphic rank than most New Zealand "greywacke" rocks, and there is no reason to explain the presence of hydrocarbons by downward migration.

According to Wellman (1956 : 13, 31), the New Zealand Geosyncline started to evert in the Middle Jurassic, when an Upper Mesozoic geosyncline was formed along the east side of the North Island, its southern end extending into Eastern Marlborough and, judged by the Upper Jurassic fossils here described, father south to North Canterbury. Throughout this eastern area indications of oil are plentiful and have generally been attributed to Upper Cretaceous rocks (Morgan, 1925; Ongley and Macpherson, 1928). At Blairlogie Gas Vent, East Wellington, Ongley (1936 : 12) found that the source of gas was a basal Upper Cretaceous conglomerate, unconformably overlying greywacke, shattered argillite, and sandstone interbedded with green and red tuffs and igneous rocks, similar to the Upper Jurassic of Cheviot, and indeed classed as Jurassic by Ongley ("Taitai Series"). Elsewhere, oil seeps and gas springs are associated with areas of indurated sediment of probably Lower Cretaceous age (Mokoiwi Mudstone of Wellman, 1956). Although geologists have generally considered such rocks too much metamorphosed to be the source of oil (Morgan, 1921 : 18, 1925 : 287) or too "indurated, slickensided, shattered, and crushed to be worth consideration as part of an oil-field" (Ongley, 1936 : 11), the evidence at Cheviot suggests that some oil traces in Wellman's Upper Mesozoic Geosyncline do in fact originate in sediments as old as

Upper Jurassic, and that some traces in Upper Cretaceous rocks (as at Blairlogie) may be due to upward migration.

The Cheviot Hills rocks are classed in the Hokonui System and have therefore been considered "subject to the whole Hokonui Orogeny" as conventionally interpreted (e.g. Cotton, 1954) but on Wellman's hypothesis they are sediments of the succeeding phase that led on to deposition of Cretaceous sediments in the restricted eastern geosyncline. This new concept in New Zealand historical geology may lead to a fresh outlook on oil-prospecting. Whatever their history, however, the Upper Jurassic rocks of Cheviot Hills remain deformed, shattered, and structurally complex so that oil exploration in them will continue to be difficult.

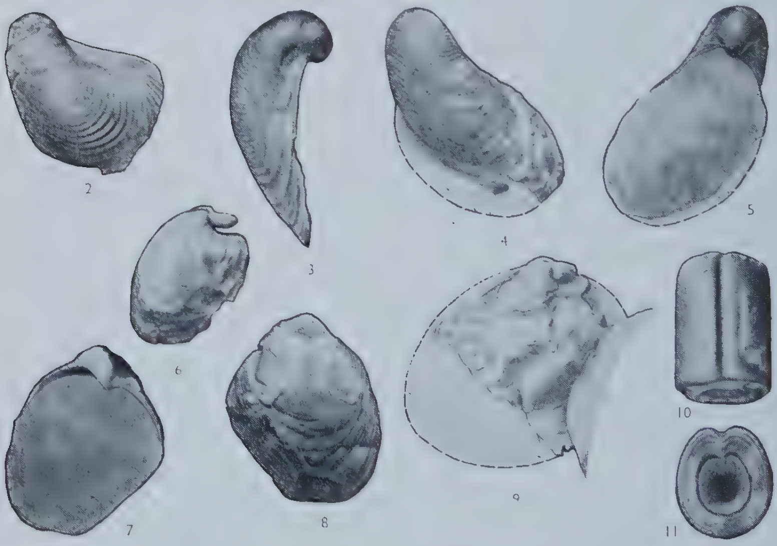


FIG. 2.—*Buchia* aff. *subpallasi* (Krumbeck). West slope, Cheviot Hills (GS 502). Coll. A. McKay, 1882. Left valve.

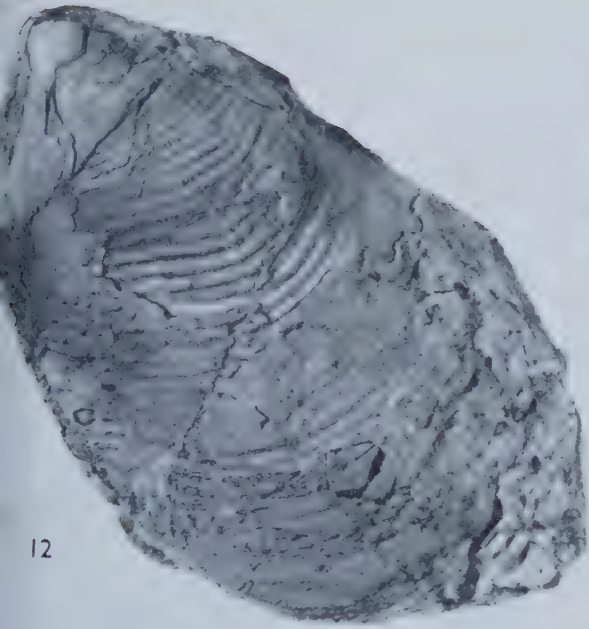
FIGS 3, 4, 5.—*Buchia* aff. *subpallasi* (Krumbeck). Gore River, Marlborough (GS 5828). Coll. G. W. Grindley and D. R. McQueen, 1953. Left valve.

FIG. 6.—*Buchia* aff. *malayomaorica* (Krumbeck). Coast south of Waiau River (GS 3441). Coll. H. E. Fyfe, 1934. Right valve.

FIGS 7, 8, 9.—*Buchia* aff. *malayomaorica* (Krumbeck). Coast south of Waiau River (GS 3446). Coll. H. E. Fyfe, 1934. Left (7, 8) and right (9) valves.

FIGS 10, 11.—*Hibolithes browni* (Marshall). Woolshed Stream, south-east of Glenkens Station (GS 3429). Coll. J. Marwick, 1934.

(*Figures natural size.*) —*R. C. Brazier, del.*



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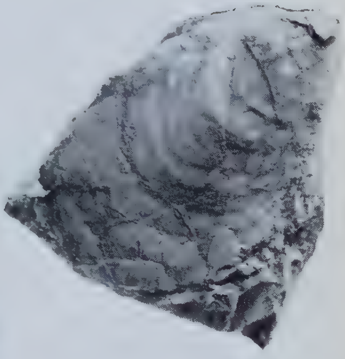

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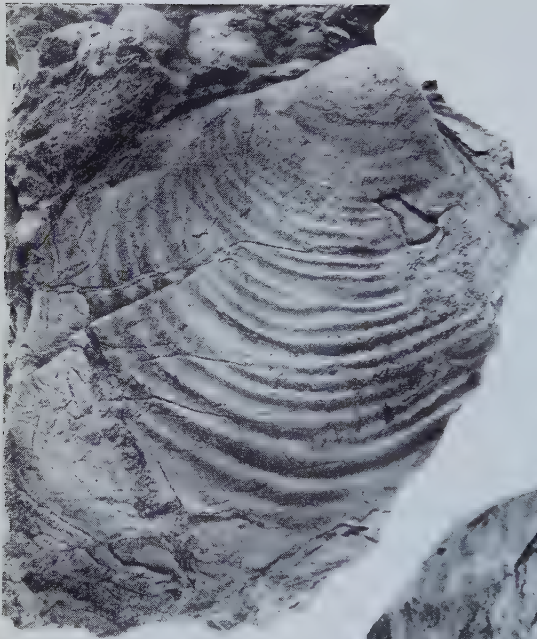
FIG. 12.—*Inoceramus* n.sp. A, ? aff. *everesti* Holdhaus. Between Mount Beautiful and coast. Coll. J. D Campbell, August, 1956. Left valve ×1.

FIG. 13.—*Inoceramus* n.sp. B, ? aff. *gracilis* Holdhaus. Between Mount Beautiful and coast. Coll. J. D. Campbell, August, 1956. Right valve ×1.

—*S. N. Beatus, photo.*

ACKNOWLEDGEMENTS

Thanks are expressed to Mr H. E. Fyfe, New Zealand Geological Survey, for permission to base a sketch map on his unpublished geological field sheets of the Cheviot Hills and to Mr J. D. Campbell, University of Canterbury, who made available his new collections of Jurassic fossils from the district. Mr Graeme R. Stevens, now at the Sedgwick Museum, Cambridge, kindly sent extracts and a photostat of Russian publications not available in Wellington. Figs 2 to 11 are from drawings by Mr R. C. Brazier, New Zealand Geological Survey, and Figs 12 to 16 from photographs by Mr S. N. Beatus, Department of Scientific and Industrial Research, Wellington. The Dominion Analyst supplied the chemical data and report quoted in the section on hydrocarbon traces.



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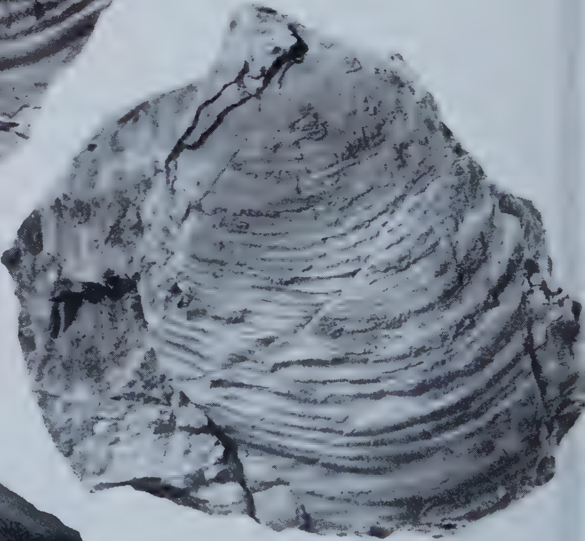

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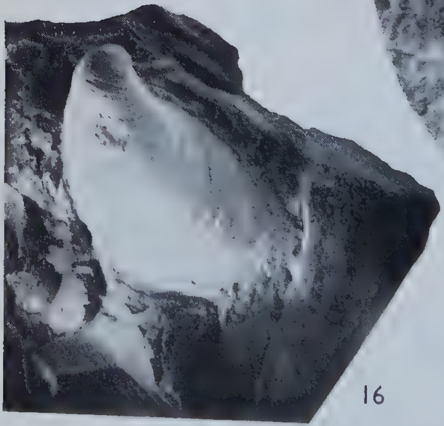

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Figs 14, 15.—*Anopaea* n.sp. Between Mount Beautiful and coast. Coll. J. D. Campbell, August, 1956. Right and left valves, ×1.

Fig. 16.—*Buchia* aff. *subpallasi* (Krumbeck). S62/528. Boulder in Woolshed Stream. Coll. J. D. Campbell, August, 1956. Left valve ×1.

—*S. N. Beatus, photo.*

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NEW ZEALAND GEOLOGICAL ABSTRACTS 1956

Compiled by B. W. Collins, New Zealand Geological Survey,
Department of Scientific and Industrial Research*

(Received for publication, 10 March 1958)

Following the recommendation of the British Commonwealth Specialist Conference on Geology and Mineral Resources (London, 1948), the New Zealand Geological Survey has compiled abstracts of New Zealand geological publications annually since 1949. In the last compilation (for 1955, published in *N.Z. J. Sci. Tech., B 38 (8),* pp. 903–24; September 1957), full bibliographic references were given to previous abstracts. The abstracts on the following pages continue the series and include the following classes:

(1) Publications (including books, bulletins, reviews, and significant letters, notes, and other comments) on geological subjects published in New Zealand.

(2) Publications dealing with or directly mentioning New Zealand geology published overseas, whether by New Zealand geologists or others.

(3) Geophysical, mining, engineering, and pedological publications having a direct bearing on New Zealand geological problems.

For convenience of reference, the papers are numbered serially, prefixed by 56 (an abbreviation for the date of their publication). They have been indexed under various branches of geology, and also, where appropriate, under the land districts of New Zealand.

The authorship of each abstract is indicated by initials or notes in parentheses.

For assistance received, the compiler thanks the following: Professor C. A. Cotton, Wellington; and Dr C. A. Fleming and Dr H. J. Harrington, and Mr D. R. Gregg, of the New Zealand Geological Survey.

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56/1—**ADKIN, G. L.**: The Seatoun Fault, Miramar Peninsular, Wellington. *Trans. roy. Soc. N.Z., 84* (*2*): 273–7, 2 figs.

A brief discussion of some debatable points connected with current interpretations of geological structure, and deformation of southern Wellington is followed by the description of a recently-recognized fault (having strong topographic expression and showing some late movement) located on the eastern side of Miramar Peninsula. (Author's abstract.)

56/2—**ADKIN, G. L.**: The Term "Jade" for New Zealand Greenstone (Note). *J. Polynes. Soc., 65* (*2*): 176–7.

Criticizes the use of the term "jade" to cover both kinds of New Zealand greenstone—nephrite (pounamu) and bowenite (tangiwai). Advocates, for precise description, the use of the correct mineralogical terms or the Maori names, and the retention of "greenstone" (or "precious greenstone") to cover both varieties. (B.W.C.) *See also* Webster, 56/106.

56/3—**ANON.**: Geology in New Zealand. *N.Z. Sci. Rev., 14* (*4*): 44.

Brief biographical notes with portraits of Dr L. I. Grange, retiring Director of the New Zealand Geological Survey, and his successor, Mr R. W. Willett. (B.W.C.) *See also* Webster, 56/106.

56/4—**ANON.**: The Coalfields of New Zealand: 1—Nightcaps-Ohai. *N.Z. Coal, 1* (*1*): 16–8, photos. 2—Waikato-Huntly. *Ibid., 1* (*2*): 16–8, photos. 3—Buller-Westport. *Ibid., 1* (*3*): 18–20, photos.

A series of popular descriptive and historical articles, illustrated with numerous new and old photographs. (B.W.C.)

56/5—**ANON.**: Mining Conference was Biggest Yet. *N.Z. Coal, 1* (*3*): 2–5, 11, photos.

An account of the Mining and Quarrying Conference held at the Otago School of Mines, Dunedin, in August 1956, with a list of papers presented. (B.W.C.)

56/6—ANON.: Kimihia—the Coalfield Under a Lake. *N.Z. Coal, 1 (3)*: 12–3, 2 figs.

A seam of sub-bituminous coal nearly 30 ft thick and extending over 80 acres is mined opencast near Huntly. The overburden is 80 to 180 ft of pumiceous silt. A stop-bank 1¼ miles long was built to expose part of a lake floor, and drainage water is also pumped from a 10-inch well 180 ft deep. (B.W.C.)

56/7—ARKELL, W. J.: "Jurassic Geology of the World." Oliver & Boyd, Edinburgh and London. xv + 806 pp., 46 pls., 102 figs.

A summary of New Zealand Jurassic geology (pp. 451–7) includes the following. The local stages are referred to as "series." Ammonites so far known from the Puaroan of Kawhia are an assemblage of Berriasellids of predominantly Berriasian (Necomian) appearance. The ammonite assemblage from the north shore of Kawhia is reminiscent of the Middle Spiti Shales (Lower Tithonian). On the south shore, *Torquatisphinctes* and *Idoceras* of strongly Mexican affinities occur, and near the base of the Heterian at Captain King's, *Idoceras* cf. *humboldti* Burkh, *Epicephalites* cf. *epigonus* (Burkh.), and squashed *Subneumayria,* all of the Mexican Lower Kimeridgian, have been collected. *Holcophylloceras* from Totara Point (now recorded also from Onewhero), previously identified as aff. *mediterraneum* is more coarsely ribbed and agrees best with *H. passati* (Boehm). (C.A.F.)

56/8—BATLEY, R. A. L.: Some Practical Aspects of Dendrochronology in New Zealand. *J. Polynes. Soc., 65 (3)*: 232–44.

An account of techniques used to date the removal of bark from ṭotara by Maoris. The difficulties of applying dendrochronology in New Zealand are emphasized, and the paper concludes with a glossary. (D.R.G.)

56/9—BATTEY, M. H.: Observations on the Structure of Far Northern New Zealand. *Rec. Auck. Inst. Mus., 4 (6)*: 309–15, 1 pl., 2 figs. (maps).

East-west fold axes due to north-south compression are important in the region north of the Bay of Islands. A later system of tear (compression) faults extends from North Cape south-east to Whangaroa Bay, coinciding with the belt of intrusion and mineralization recognized by Hector. There is thus evidence for the occurrence of two epochs of compression since the middle Tertiary, in the first of which pressure was directed from north and south, whereas in the second it was from east and west. Such successive foldings at right-angles have previously been suggested by Lillie in other parts of New Zealand. The presence of fold-axes striking north-west in the Far North was not confirmed, except in so far as the New Zealand ridge as a whole may represent a geanticline. (From author's abstract.) *See also* Harrington and Hay, 56/58.

56/10—BATTEY, M. H.: The Petrogénesis of a Spilitic Rock Series from New Zealand. *Geol. Mag., 93 (2)*: 89–110.

Well-preserved spilites from Doubtless Bay, Mount Camel, and Great Island in the Three Kings Group show marked affinities with certain tholeiites in texture, chemistry, differentiation-trend, and in some aspects of their mineralogy. (C.A.F.) *See also* Harrington and Hay, 56/58.

BAULIG, H.: *See* Cotton, Baulig, and Wallace, 56/32.

56/11—BAUMGART, I. L.; HEALY, J.: Recent Volcanicity at Taupo, New Zealand. *Proc. 8th Pacif. Sci. Congr. (Manila, 1953), 2*: 113–27.

A 35 ft section through the "Taupo sequence of volcanic showers" in a quarry three miles south-east of Taupo can be divided into 27 main members. A map shows the distribution and thickness of 4 members around the centres of eruption.

The lower 14 ft of the section consists of 7 members, some separated by fossil topsoils and some containing weathered andesitic ash probably of the Tongariro series of showers. The lowest member, resting on the Waitahanui Breccia, has a ^{14}C age of about 9,000 years, and the top of this portion of the section is a fossil soil with a ^{14}C age of 3,100 years B.P. (before present).

The middle 10 ft of the section consists of pumice lapilli and ash beds each only a few inches thick.

The upper 11 ft of the section is divided into 6 members, in upward order: Hatepe lapilli member, an unnamed member, Rotongaio ash member, Taupo lapilli member, Taupo rhyolite block member, and Upper Taupo pumice members, which are separated by only short time intervals, and were erupted from several vents as huge glowing avalanches, nuées ardentes, and ash clouds. A sample from the Taupo rhyolite block member 4 miles north of Wairakei has a ^{14}C age of 1,700 years.

The history determined from the quarry section and from mapping of the surrounding region is that eruption of the lower 7 members commenced at about 9000 B.P. (7050 B.C.) and was followed by a non-eruptive period sufficiently long for the formation of a soil layer with a ^{14}C age of 3100 B.P. (1150 B.C.). The non-eruptive period was interrupted locally by the thin ash showers of the middle of the section, but elsewhere continued until a little before 1700 B.P. (250 A.D.), when a series of violent pumice eruptions commenced. (H.J.H.)

56/12—Bell, Shona; Harrington, H. J.; McKellar, I. C.: Lower Mesozoic Plant Fossils from Black Jacks, Waitaki River, South Canterbury. *Trans. roy. Soc. N.Z., 83 (4)*: 663–72, 4 figs.

In Part 1 (Geology, by Harrington and McKellar, pp. 663–5), the geology of an area on the north-east bank of the middle Waitaki River is briefly described, with a columnar section of about 10,000 ft of greywacke, argillite, and conglomerate. In Part 2 (Paleontology, by Bell, pp. 666–72), the plant fossils found are listed, and the following new species are described and figured: *Chiropteris biloba, C. waitakiensis,* and *Linguifolium waitakiense.* Most of the genera are common in Triassic and Jurassic (particularly Rhaetic) floras in other parts of the world. (Author's abstract extended.)

Bell, Shona: *See also* Wood, 56/109.

56/13—Benson, W. N.: Cambrian Rocks and Fossils in New Zealand. Preliminary note *in* "El Systema Cambrico, su Paleogeografia y el Problema de sur Base," ed. J. Rodgers. Vol. 1, Pt. 2 (Australia, America), pp. 285–8.

In Cobb Valley, north-west Nelson ,a small area of sediments contains interstratified fossiliferous Cambrian limestone. The fossiliferous lenses are enclosed in argillite, siltstone, greywacke, and perhaps conglomerate, separated by faults. Determinations by J. C. Stubblefield, O. P. Singleton, A. A. Opik, and F. H. T. Rhodes are cited, including trilobites, sponges, brachiopods, and gastropods. The trilobites suggest late Middle Cambrian age, and are related to those of Western Queensland, Manchuria, and the Baltic region. (C.A.F.)

56/14—Billinghurst, W. M.; Nicholson, D. S.: An Investigation into the Manufacture of Fused Calcium-Magnesium Phosphate Fertilizer in New Zealand. *N.Z. Dep. sci. industr. Res. Bull. 119.* 66 pp., 10 figs.

Includes (pp. 8–12, 14–29) a discussion on the location, quantity available, and working conditions of the following raw materials: dunite (Greenhills, near Bluff), serpentine (Mossburn, D'Urville Island, and Te Kuiti), and silica (quartz gravels from Awarua, Woodend, and Pebbly Hills, near Bluff; quartzite and quartz sand near Nelson; reef quartz near Tauranga; and quartzite near Whangarei). Chemical analyses are included, as well as simplified geological maps of small areas at Greenhills (Bluff) and Dun Mountain (Nelson). Phosphate rock is available from Nauru and Ocean Islands. (B.W.C.)

56/15—Bottomley, G. A.: Seiches on Lake Wakatipu, New Zealand. *Trans. roy. Soc. N.Z., 83 (4)*: 579–87, 5 figs.

The principal features observed in a series of recordings extending over 300 hours are described. The fundamental period (52 min.) and the first harmonic (27 min.) are predominant, and at one site there was a well-developed oscillation of 4·28 minutes. All the phenomena observed can be explained by seiche action. (From author's abstract.) *See also* 56/16.

56/16—Bottomley, G. A.: The Free Oscillations of Lake Wakatipu, New Zealand. *Trans. Amer. geophys. Un., 37 (1)*: 51–5, 2 figs.

The period of vibration and the surface shape for the fundamental and several harmonics for free longitudinal oscillations of Lake Wakatipu were deduced from the behaviour of a laboratory model. (From author's abstract.) *See also* 56/15.

56/17—Boucot, A. J.; Gill, E. D.: *Australocoelia,* a New Lower Devonian Brachiopod from South Africa, South America, and Australia. *J. Paleont., 30 (5)*: 1173–8, 1 pl., 1 fig.

Contains a brief reference to the paleogeography of the New Zealand region, quoting R. S. Allan (1935 and 1947) and A. L. du Toit (1937). (B.W.C.)

56/18—Bradley, J.: The Geology of the West Coast Range of Tasmania: Part 2—Structure and Ore Deposits. *Pap. roy. Soc. Tasm. 90*: 65–129, 2 pls., figs. 5–17.

Contains brief references to New Zealand on pp. 66 and 72, and a fuller description (pp. 100–4) of New Zealand structures (asymmetric anticlines, tilted fault blocks bounded by dextrally transcurrent faults) and comparisons with Tasmania and the Basin Range region of the U.S.A. in California and Colorado. The southern Wellington, Manawatu, and Dun Mountain districts of New Zealand are specifically mentioned. (B.W.C.))

56/19—Brothers, R. N.: The Structure and Petrography of Greywackes Near Auckland, New Zealand. *Trans. roy. Soc. N.Z., 83 (3)*: 465–82, 2 pls., 2 figs.

Structural analyses of deformed Permian-Triassic greywackes and argillites at Tawaharanui Peninsula and Bream Tail show that these basement rocks have been affected by at least two periods of folding. The oldest and dominant structural direction is identified from axes of minor folds and intersections of shear planes. In successions of thick sandstones near Auckland, this axis is horizontal and undeformed with a north-and-south trend, but in areas of argillite a younger oblique axis of folding directed west-south-west has modified the earlier structures. The sandstones and argillites have undergone low-grade regional metamorphism and contain quantities of such crystalloblastic minerals as albite, quartz, sphene, epidote, prehnite, stilpnomelane, chlorite, sericitic mica, and occasionally calcite and hornblende. The rocks are compared with subzone Chlorite 1 schists of Otago. (Author's abstract.)

56/20—Brown, D. A.: Report on Geology of Upper Shotover, *in* "Shotover River Survey (Upper Catchment)." *Otago Catchment Board Bull. 1,* pp. 8–15, geol. map.

The area, situated near the axis of the "Otago Anticline," is composed mainly of micaceous schists of the Chlorite zone, the foliation planes having an average dip of 20 to 25° west. Three major sub-meridional faults traverse the area—the Moonlight Fault with involved marine Tertiary rocks, the Shotover Fault, and the Polnoon Fault. In the valleys there is much drift material in the form of terraces up to 200 ft above present river level and wide alluvial fans. The relative scarcity of glacial features may be accounted for by the profound erosion that has occurred since Pleistocene times. From the distribution of pebbles, igneous rocks of the lamprophyre suite occur chiefly in the divide between the Shotover and Matukituki Rivers. The terrace gravels were formerly worked for gold. (B.W.C.)

56/21—Buckenham, M. H.; Rogers, J.; White, C. C.: The Flotation of Talc from the Talc-Magensite of the Cobb Valley, Nelson. *N.Z. J. Sci. Tech., B, 37 (4)*: 437–44, 1 fig.

For the full development of the extensive deposits of talc-magnesite in the Cobb Valley, satisfactory methods of separation of the talc and magnesite must be established. The paper describes the results of flotation tests on samples from the No. 2 lens. A concentrate containing 98% talc was obtained. (From author's abstract.)

56/22—BUNT, J.: Living and Fossil Pollen from Macquarie Island. *Nature, 177 (4503)*: 339.

Lignites from fluvoglacial deposits classed as postglacial by Mawson contain pollens of a flora completely unlike the present Macquarie Island flora and thus probably a remnant of the preglacial flora. The 17 main pollen types do not include gymnosperms of *Nothofagus,* and show no definite relationships with New Zealand Tertiary plant microfossils, but lack of detailed descriptions of New Zealand composite pollens prevents comparisons in this group. The fossil flora may be closely related to the Tertiary floras of the Antarctic. (C.A.F.)

56/23—CAMPBELL, J. D.: The Otapirian Stage of the Triassic System in New Zealand: Part 2. *Trans. roy. Soc. N.Z., 84 (1)*: 45–50, map.

A basal Otapirian fauna is established for the Dipton-Southern Taringatura Hills region. Fossil assemblages from sequences in the Kaihiku Ranges and at Nugget Point are shown to have forms in common with this fauna. The Otapirian faunal succession at Kawhia is described, and the distribution of Jurassic stages illustrated by means of a map. Species comprising the basal Otapirian fauna and an upper Otapirian fauna are listed. (Author's abstract modified.) *See also* 56/24.

56/24—CAMPBELL, J. D. MCKELLAR, I. C.: The Otapirian Stage of the Triassic System of New Zealand: Part 1. *Trans. roy. Soc. N.Z., 83 (4)*: 695–704, 1 fig.

Previous literature on the "Otapiri Series" is reviewed; the Otapirian Stage is defined, *Spiriferina (Rastelligera) diomeda* Trechmann being selected as the key fossil; and the sequence at the type locality, Otapiri Valley, western Hokonui Hills, Southland, is described. Fossil species that have been described from Otapirian localities in New Zealand are listed. (Author's abstract extended.) *See also* 56/23.

CLARK, R. H.: *See* Turner, Griggs, Clark, and Dixon, 56/98.

56/25—COLLINS, B. W.: Underground Water Supplies for Irrigation. *Proc. Lincoln College Farmers' Conf., 1956,* pp. 70–85, 4 figs.

The advantages of ground water are reviewed and the principles of its occurrence described. The various types of water-bearing formations in New Zealand are then dealt with. A discussion of the different types of wells and the factors affecting their yield and usefulness leads to a brief description of the hydraulics of wells and pumps. Various hydrological terms are defined. The practice of divining well sites is dismissed as useless. The ground-water areas of New Zealand are briefly described and shown on a map, with special reference to the areas where supplies of several hundred gallons a minute are likely to be most readily obtained. The most important aquifers are the young alluvial gravels of the piedmont plains and river valleys. There is great scope for the increased use of ground water for irrigation in many places. (B.W.C.)

56/26—COLLINS, B. W.: Petroleum Exploration in New Zealand, 1955. *A'asian Oil and Gas J., 2 (10)*: 4–7, map.

At the end of 1955, the total area covered by petroleum prospecting licences was 11,715 square miles, 8,901 square miles being in the North Island.

The North Otago Development Co. suspended drilling a well near Oamaru at 2,810 ft. after penetrating an unexpectedly thick section of tuffaceous sandstone (Early Tertiary).

Advances in Upper Cretaceous and Tertiary stratigraphy have improved understanding of the structure and oil possibilities of the East Coast and Taranaki areas of the North Island. A re-study of the Foraminifera in cores from the Midhirst well (Taranaki) by Hornibrook leads to the belief that the well penetrated only 80 ft of the Mahoenui Formation, not 3,000 ft as formerly considered. This formation has long been thought the best potential oil source in Taranaki and has not yet been adequately tested by drilling.

Geophysical work included gravimetric and seismic surveys, a new domal structure being found at Ahaura, near Greymouth. (B.W.C.)

56/27......COTTON, C. A.: Coastal History of Southern Westland and Northern Fiordland. *Trans. roy. Soc. N.Z., 83 (3)*: 483–, 3 figs.

Episodes in the history of the compound coast of southern Westland are: (1) monoclinal tectonic development; (2) morainic progradation; (3) transverse deformation (attributable to compression associated with movement on the Alpine Fault); (4) glacial excavation of fiord-like valleys; (5) progradation of embayments, filling of fiords, and a general smoothing of the outline. These events are independent of, or supplementary to, the changes that must have been brought about by downward and upward movements of ocean level resulting from the Pleistocene world-wide glacierizations. (From author's abstract.)

56/28—COTTON, C. A.: Hawke Bay Coastal Types. *Trans. roy. Soc. N.Z., 83 (4)*: 687–94, 4 figs.

Recent transverse deformation of the soft-rock shores of Hawke Bay has produced anticlinal upwarpings with seaward pitch alternating with synclinal lowlands. One of the anticlinal salients, at Cape Kidnappers, has been trimmed back to a sharp cusp with outlying stacks, affording an example of youth in the development of a coast of transverse deformation (Kidnappers type). Another anticlinal salient, at the mouth of the Mohaka River, has been entirely destroyed by marine erosion, leaving a straight cliffed coast: this is an example of full maturity (Mohaka type).

Cyclic treatment of sequential development of a coast of transverse deformation is generally applicable not to such a complex coast as a unit, but to segments of it that may be classed individually as coasts of emergence, submergence, etc. This is especially so in hard-rock terrains. The cyclic transformation that has affected the Hawke Bay coast as a whole is attributed to softness of terrain, exceptional susceptibility to marine erosion, and the consequently fast tempo of erosional development. (From author's abstract.)

56/29—COTTON, C. A.: Geomechanics of New Zealand Mountain-building. *N.Z. J. Sci. Tech., B, 38 (3)*: 187–200, 6 figs.

Like the mountains of Asturas (Northern Spain), many parts of New Zealand exhibit the effects of superposed orogenies—the earleir alpino-type, but the later necessarily Germano-type because of earlier cratonization of the terrain. A theory is suggested that the later orogeny, or block faulting (Kaikoura orogeny) was due to stresses set up by lateral drift along the 'transcurrent fault zone" defined by Wellman, which is probably a primary feature marking the course of a "geosuture" (H. Cloos), or "regmatic joint" (Sonder). If this is so, the Alpine Fault cannot have been produced by compressive stress in the crust, but must be a true "tear fault" caused by subcrustal movement. Probably other transcurrent faulting in New Zealand is due also to drift originating beneath the crust. (Author's abstract slightly modified.)

56/30—COTTON, C. A.: The Question of Polar Wanderings. *N.Z. Sci. Rev., 14 (7)*: 92–3.

A review of theories and opinions put forward during the last 50 years to explain the distribution of past glaciations and the anomalies of paleomagnetism. The possibility of lateral movement of the earth's skin over the substratum is now widely though not universally accepted. (B.W.C.)

56/31—COTTON, C. A.: Rias *Sensu Stricto* and *Sensu Lato*. *Geog. J., 122 (3)*: 360–4.

A review of the various usages of the term "ria" by Richtofen, Penck, Gulliver, Suess, Johnson, de Martonne, and others leads to the suggestion that, though it might make for convenience to include all ria-like bays and gulfs in a broad category of "rias," a more conservative and strictly defensible course would be to restrict the term to those conforming with Richtofen's original definition. This applied only to the drowned features of coasts with transverse folded structure. Examples are cited from various parts of the world. The drowned valleys of the Galician-Asturian coast of northern Spain are true rias, but the Marlborough Sounds of New Zealand are drowned insequent valleys without recognizable control by structure and are ria-like features or rias *sensu lato*. (B.W.C.)

56/32—Cotton, C. A.; Baulig, H.; Wallace, W. H.: Geomorphology, Geomorphography, Geomorphogeny, and Geography. *N.Z Geogr., 12 (1)* : 89-93.

Comments by Cotton and Baulig on an article, "New Zealand Landforms", by Wallace (abstract 55/102) with Wallace's replies. Cotton and Baulig both place much importance on the genetic study and explanatory description of landforms: Wallace considers for many geographical purposes an objective description of surface configuration sufficient. (B.W.C.)

56/33—Cotton, C. A.; Tricart, J.: Discussion à propos de l'analyse d'un ouvrage. *Rev. Geomorph. Dynam., 7* : 148-9.

A comment by Cotton provoked by a review by Tricart of a paper by Cotton and Te Punga (abstract 1955/26—*N.Z. Geogr., 11 (1)* : 72-5), together with a reply by Tricart.

Couper, R. R.: *See* Wood, 56/112.

56/34—Davenport, A. E.: Power Probabilities. *N.Z. Sci. Rev., 14 (7)* : 88-92.

This review of the probabilities of power development in New Zealand includes discussion of coal-fired steam stations, geothermal stations, and the factors affecting the laying of a submarine cable across Cook Strait. (B.W.C.)

56/35—Dell, R. K.: The Fresh-water Mollusca of New Zealand. Parts 2 and 3. *Trans. roy. Soc. N.Z., 84 (1)* : 71-90, 7 figs.

Includes descriptions of sub-fossil forms of *Simlimnea* (p. 80) and *Physastra* (pp. 89-90). (B.W.C.)

56/36—Dell, R. K.: A Synopsis of the Nuculanidae, with Check Lists of the Australasian Tertiary and Recent Species. *Rec. Dom. Mus.* [*N.Z.*] *2 (3)* : 123-4.

Includes check list of New Zealand Tertiary species. (C.A.F.)

56/37—Dell, R. K., 1956: Some New Zealand Subfossil Land Mollusca. *Rec. Dom. Mus.* [*N.Z.*], *2(3)* : 135-44, 4 figs., map.

Description of Quaternary land snails from limestone caves and swamps on either side of Cook Strait, and discussion of paleogeographic implications. (C.A.F.)

56/38—Dell, R. K., 1956: Some New Off-shore Mollusca From New Zealand. *Rec. Dom. Mus.* [*N.Z.*], *3 (1)* : 27-59, 69' figs (on 6 pp.)

Includes the first Recent records of *Linucula*, *Cardiomya*, and *Tioria*, previously known from the New Zealand Tertiary. Discusses fossil species of *Globisinum*, *Coluzea*, and *Eucominia*. (C.A.F.)

56/39—Dell, R. K., 1956: The Archibenthal Mollusca of New Zealand. *Dom. Mus.* [*N.Z.*] *Bull. 18.* 245 pp.

Includes many references to the systematics of Tertiary mollusca; a record of the deep-water genus *Euciroa* from the Tertiary of Tarakohe, Nelson; the first living species of the genera *Paramussium*, *Plea*, *Waipaoa*, *Teremelon*, *Scaphander*, and *Planipyrgiscus*, previously known only as Tertiary fossils; and comment on the depth of deposition of Nukumaruan and Castlecliffian sediments. The depth ranges of benthic species are analysed, and the relationships and origins of the fauna and some paleontological implications discussed. (C.A.F.)

56/40—Dibble, R. R.: Earthquake Risks in the Wellington Area. *N.Z. Sci. Rev., 14 (8)* : 109-12, 4 figs.

Wellington has experienced greater and more numerous desructive earthquakes than any other town in New Zealand. Major earthquakes have tended to occur on the main active faults, which are most crowded near Wellington. It is estimated that one destrcutive earthquake will occur on the average every 40 years in this district. Most will be of intensity 7 or 8 at Wellington, but rarely the intensity may reach 11. (B.W.C.) *See also* 56/68.

56/41—Dibble, R. R.; Suggate, R. P.: Gravity Survey for Possible Oil Structures, Kotuku-Ahaura District, North Westland. *N.Z. J. Sci. Tech., B. 37 (5)* : 571-86, 4 figs. (maps and sections).

A gravity anomaly map of the Kotuku-Ahaura district in the Grey-Inangahua depression and geological interpretations of profiles across the depression are presented. The depression is shown to contain two major syncline — Grey Valley and Mawheraiti Synclines — arranged "en echelon" and separated by an anticline on which there is a minor closed structure — the Ahaura Dome — 12 miles northeast of the oil seepages at the Kotuku Dome. The strata at the Ahaura Dome, inferred from the geological history, are thought to contain no impermeable layers that may trap oil, but, as this is not certain, a test drillhole is considered desirable. (Authors' abstract.)

56/42—Elphick, J. O.: A Users Directory of New Zealand Coals. *N.Z. Dep. sci. industr. Res. Inform. Ser. No. 10,* 19 pp., 2 maps.

Intended to provide users of New Zealand coals with information of use in their selection and utilization, this bulletin presents four tables of analyses and properties of coal from each working mine in the country. The values are based on analayses by the Dominion Laboratory of face and run-of-mine samples taken mainly by officers of the N.Z. Geological Survey. Moisture content, volatile matter, ash, sulphur, calorific value, crucible swelling number, rank, and output in tons are listed for the production of all mines working in 1955. Notes includes definitions and explanations of terms used and examples of calculations of calorific value at any given moisture and/or ash content, optimum moisture content, and flue gas losses. (B.W.C.)

56/43—Evison, F. F.: The Seismic Determination of Young's Modulus and Poisson's Ratio for Rocks in Situ. *Geotechnique, 6 (3)* : 118-23, 5 figs.

Experiments with an electrically driven vibrator generating shear and compressional seismic waves in ignimbrite county rock and in the concrete of a dam at Whakamaru, New Zealand, are described. From the velocities measured the elastic constants were calculated. (B.W.C.)

56/44—Evison, F. F.; Reilly, W. I.: Deformation of Strata in Board-and-Pillar Coal Mines. I—Convergence Observations. *N.Z. J. Sci. Tech., B, 37 (6)* : 716-30, 11 figs. II—Model Analysis. *Ibid., B, 38 (2)* : 129-38, 4 figs.

Convergence recorders have been used to study the strata movements in New Zealand coal mines since 1953. An elaborate series of measurements in one mine is consistent with the theory of overburden support by a pressure arch that forms around the opening and expands as the strata deform. Two types of deformation are recognized. During development of a mine the movement is regular and is attributed to plastic flow of the clay-like material under the coal seam. During the later stages of pillar extraction the movement is irregular and more rapid and is believed to originate in the crushing of pillar coal.

A four-element spring-dashpot model gives a useful representation of the deforming strata adjacent to a coal mine, supports the interpretation of the two types of convergence recognized, and relates the critical rate of convergence to the crushing strength of coal in the rib-zone. (B.W.C.)

56/45—Farrell, B. H.: The Geography of Power Resources in the Waikato Region. *N.Z. Geogr., 12 (2)* : 133-54, 14 figs.

In the Waikato River basin sub-bituminous coals, water, and underground steam are all being exploited to provide energy for farms, factories, and homes. The area contains most of the known major power resources of the North Island, and the combination of coal, water, and geothermal steam may possibly be unique. The article attempts to describe this power complex, assess its character and functions, and evaluate the significance of the region to New Zealand. There is a brief description of the coal measures of the Lower Waikato area (pp. 144-6). (B.W.C.)

56/46—Fell, H. B.: New Zealand Fossil Asterozoa. 2—*Hippasteria antiqua* n.sp., from the Upper Cretaceous. *Rec. Canterbury [N.Z.] Mus., 7 (1)* : 11-2, 1 pl.

The new species was collected on Cotswold Station, Omihi, from a boulder in the bed of a tributary of Motunau River, North Canterbury, and is attributed to the Senonian on the authority of R. S. Allan. Hippasteria has not hitherto been recorded as a fossil and is not otherwise known from Australasia. (C.A.F.)

56/47—Fieldes, M.; Walker, I. K.; Williams, P. P.: Clay Mineralogy of New Zealand Soils. Part 3—Infra-red Absorption Spectra of Soil Clays. *N.Z. J. Sci. Tech., B, 38 (1)* : 31-43, 1 fig.

Infra-red absorption data are presented for 19 clays from typical New Zealand soils. Constituents identified are hydrous micas, kaolinite, halloysite, crystalline silica, amorphous silica, hydrous aluminium oxides, geothite, allophane, and calcite. (From authors' abstract.)

56/48—Forbes, L. M.: Ferrar of the Glacier. *Antarctic, 1 (4)* : 95-8.

Biographical details of H. T. Ferrar (of the N.Z. Geological Survey) by his son-in-law with the co-operation of Mrs Ferrar, mostly with reference to his work in the Antarctic, 1901-4. (B.W.C.)

56/49—Francis, G. H.: The Serpentinite Mass in Glen Urquhart, Inverness-shire, Scotland. *Amer. J. Sci., 254 (4)* : 201-26, 2 pls., 5 figs.

Includes powder X-ray diffraction patterns of New Zealand antigorite from the Griffin Range and Mikonui, and refers to New Zealand sepentines, dunite, etc. (B.W.C.)

56/50—Gage, M.: Note on Tertiary Rocks in the Waimakariri Valley, Canterbury. *N.Z. J. Sci. Tech., B, 37 (5)* : 606-9, 1 fig.

The continuation south-west of the Waimakariri River of the Esk Valley infaulted Tertiary outlier shows angular unconformity between the Brechin (Awamoan or Altonian) and Esk (Whaingaroan to Duntroonian) formations. There is local overlap of the Brechin formation onto pre-Cretaceous undermass. Scattered outcrops suggest the existence of a further strip of infaulted Cretaceous and Tertiary beds between and sub-parallel with the Esk Valley and Harper Valley structural depressions. (Author's abstract.)

56/51—G[age], M.: A Backward Glance. [Review of "New Zealand Geomorphology" by C. A. Cotton (1955)]. *N.Z. Sci. Rev. 14 (1-2)* : 13.

As a convenient assemblage of reprints this volume is most valuable. The reviewer points out, however, that the papers were written against a background of geological thinking very different from that of today, and claims that the footnotes and insertions have failed to bring them up to date. He also criticizes the title of the book as possibly misleading (to which the author replied in a brief letter to the editor, *Ibid., 14 (5)* : 60. (B.W.C.)

56/25—Gage, M.: Australian and New Zealand Research in Eustasy—Part I: New Zealand. *Aust. J. Sci., 19 (1)* : 18.

A short review of recent publications and papers presented at scientific meetings, written as part of an A.N.Z.A.A.S. Standing Committee report. (B.W.C.)

56/53—Golson, J.: New Zeaalnd Archaeological Society. First Annual Conference. *J. Polynes. Soc., 65 (1)* : 77-81.

A summary of the proceedings of the conference. The following papers of geological interest were presented: Radiocarbon Ageing in New Zealand (T. A. Rafter); Tree-ring Dating (R. E. Bell); Geological Techniques in Dating New Zealand's Prehistory (D. Kear); Pollen Analysis and Archaeology (W. F. Harris); Forest History (P. J. McKelvey); A Conchologist's Contribution to New Zealand Prehistory (A. W. B. Powell); Soil Science and New Zealand Prehistory (N. H. Taylor); and Petrological Analysis of Maori Stone Tools (R. N. Brothers). (D.R.G.)

56/54—GRANGE, L. I.: Prospecting for Radioactive Minerals in New Zealand. *N.Z. Dep. sci. industr. Res. Inform. Ser. No. 8.* 32 pp., 3 figs., 2 geol. maps.

A revised edition of a publication issued in 1954 (see abstract, 1954-39). Information on the uranium-bearing lode discovered in the Buller Gorge is included.

56/55—GREGG, D. R.: Eruption of Ngauruhoe, 1954-1955. *N.Z. J. Sci. Tech., B, 37 (6)* : 675-88, 9 figs.

The andesite volcano Ngauruhoe, in the centre of the North Island, erupted from May 1954 to March 1955. There were ten main lava flows, and the volume of lava emitted was of the order of eight million cubic yards. The period of lava emission was characterized by prolonged lava-fountaining, which built up a spatter-and-cinder cone within the old crater. Hot avalanches accompanied some of the lava flows. Ash emission continued intermittently throughout the eruption, but reached a peak about the end of September. (Author's abstract.)

56/56—GREGG, D. R.: Maori Rock-Paintings at Lake Tarawera, New Zealand. *J. Polynes. Soc., 65 (4)* : 364-6, map and fig.

Rock-paintings on a face of Haparangi Rhyolite are considered to be older than the eruption of 1886 because they are partly covered by a lake terrace formed during a period of high water level between 1886 and 1904. (B.W.C.)

56/57—HALCROW, HEATHER, M.: The Geology of Waiheke Island, Auckland. *Trans. roy. Soc. N.Z., 84 (1)* : 51-69, 2 pls., 4 figs.

The rocks are mainly greywacke sandstones and argillites, interbedded with cherts, jaspilities, and fine-grained volcanic rocks with some pillow structures. These are named Waiheke Formation and belong to the Undifferentiated Jurassic-Triassic-Permican of Willett (1948). Over the greater part of the island the attitude is fairly constant, with average strike 7° and dip usually west at about 50-60°. Sandstones and mudstones with intercalated pockets of sandstone and conglomerate containing macrofossils belong to the Waitemata Formation (Altonian, Lower Miocene) and occur at the western end of the island. Tertiary andesite breccias covered by boulders of Pleistocene basalt form a cap on the greywackes in the north-east. Pleistocene deposits consist of sands, muds, and gravels forming valley flats and raised beaches that contain occasional shell layers. (From author's abstract.)

56/58—HARRINGTON, H. J.; HAY, R. F.: The Geology of Mount Camel, Northland. *N.Z. J. Sci. Tech., B, 38 (2)* : 89-96, 4 figs.

A succession of 100 ft of indurated sandstone and siltstone (Mount Camel Formation) overlain by 700 ft of intermediate and acid lavas. (Houhora Formation) is probably no younger than Turonian and no older than Jurassic. It can be correlated with similar rocks at Three Kings Islands and Rangiawhia Peninsula. Quaternary and Holocene rocks covering most of the district consist mainly of dunes and water-bedded sands. (Author's abstract.) *See also* Battey, 56/9.

56/59—HARRINGTON, H. J.; MCKELLAR, I. C.: A Preliminary Account of Layering in Gabbroic Rocks at Bluff Peninsula, Southland. *N.Z. J. Sci. Tech., B, 38 (2)* : 103-8, 3 figs. (incl. geol. map).

Rhythmic layering and igneous lamination in parts of a gabbro mass at Barracouta Head, Bluff Peninsula, are described and their origin is discussed. Peridotit and pyroxenite masses are associated with the gabbro, and their distribution suggests that they might be part of a layered intrusion that has been folded. (Authors' abstract.)

HARRINGTON, H. J.: *See also* Bell, Harrington, and McKellar, 56/12.

HARRIS, J. W.: *See* Wood, 56/112.

56/60—HAY, R. F.: The Relationships of the Argillaceous Limestones and Greensands at Pahi Peninsula, North Auckland. *N.Z. J. Sci. Tech., B. 38 (2)* : 69-75, geol. map.

A review of the literature and a re-examination of the Pahi section has resulted in a re-interpretation of the stratigraphic sequence. The author's view is that an upper argillaceous limestone of Whaingaroan-Waitakian age (lower to mid-Oligocene) grades down into Whaingaroan and Runangan (upper Eocene) glauconitic mudstones and conglomerates, which unconformably overlie massive pebbly fossiliferous Bortonian (mid-Eocene) greensands, which grade down through a zone of interbedded greensands and argillaceous limestone into argillaceous limestone, also of Bortonian Age. The importance of the Pahi section in North Auckland stratigraphy is stressed.

Argillaceous limestone in North Auckland had previously been considered to belong to only one period of deposition. The recognition of argillaceous limestones of two periods has been found to be of wide application. The conglomerates and glauconitic mudstones are the equivalents of the North Auckland coal measures. (Author's abstract extended.)

HAY, R. F.: *See also* Harrington and Hay, 56/58.

56/61—HEALY, J. (ed.): Report of the Standing Committee on Volcanology. *Proc. 8th Pacif. Sci. Congr. (Manila, 1953), 2* : 7-79.

A statement of the committee's work by the chairman (J. Healy) is followed by members' reports of eruptions in Pacific lands between 1949 and 1953, with references to literature. There is also a list of names and addresses of volcanologists in Pacific countries with their past and present interests. The New Zealand section (pp 27-30), written by Healy, contains references to Ngauruhoe, Ruapehu, White Island, Tongariro National Park, geothermal investigations, and the chronology of recent volcanism. (H.J.H. and B.W.C.)

56/62—HEALY, J.: Preliminary Account of Hydrothermal Conditions at Wairakei, New Zealand. *Proc. 8th Pacif. Sci. Congr. (Manila, 1953), 2* : 214-27.

A summary of the first few years' investigation of the geothermal area at Wairakei, near Taupo. A total of 16 prospecting drill-holes and 8 production drill-holes have been put down to a maximum depth of 3200 ft to tap steam for a proposed electric power station. The saturated steam in the hottest channels is produced by constant boiling of water at temperatures appropriate to the pressure at a given depth less the pressure of gas present. Total heat flow is 130,000 Cal./sec., and the discharge of steam and hot water is more than twice the annual rainfall on the total area of 7 square miles. Steam is probably derived from a magmatic source, and the minimum quantity required is 152 kg./sec. (H.J.H.)

56/63—HILL, DOROTHY; LEED, HEATHER: Paleozoic Corals from New Zealand. *N.Z. geol. Surv. pal. Bull. 25.* 24 pp., 5 pls., 4 figs.

Part 1. The Devonian Corals of Reefton, New Zealand, by D. Hill (pp. 5-14, 2 pls., 1 figs.)

All corals known from Reefton are considered. A new genus, *Tipheophyllum* (type species *Eridophyllum bartrumi*), and two new species, *Hexagonaria allani* and *Thamnopora reeftonensis*, are described. Only two species are common to New Zealand and Australia. The age of the dark impure limestone with corals is deduced to be early Couvinian, or perhaps topmost Emsian.

Part 2. Permian Reef-building Corals from North Auckland Peninsula, by H. Leed (pp. 15-23, 3 pls., 3 figs.)

Two species of reef-building corals are described, members of the genera *Waagenophyllum* and *Wentzelella*. *Waagenophyllum novaezelandiae* is related to mid-Permian species from Japan and America. *Wentzelella maoria* is a member of a group of species recorded from the Permian of eastern and southern Asia. (Authors' abstracts.)

HILL, M. J.: *See* Moody and Hill, 56/76.

HORNIBROOK, N. de B.: *See* Wood, 56/112.

56/64—HOUGH, J. L.: Sediment Distribution in the Southern Oceans Around Antarctica. *J. Sed. Petrol. 26 (4)* : 301-6.

A map of Antarctic seas on a polar projection includes the New Zealand region and shows the types of bottom sediments from 500 stations reported in the literature before 1947. In general, glacial marine sediments coincide with the area of pack ice, with diatom ooze between the pack ice and the Antarctic convergence. North of the convergence there is red clay in deeper water, calcareous ooze in shallower, and "terrigenous" sediments near shores, including New Zealand and the Chatham Rise. The boundaries between sediment zones are sensitive to climatic changes, and several core samples have shown two or more types of sediment within a few feet of the surface. Three Ross Sea cores dated by a radioactivity method contain alternations of glacial marine and non-glacial sediments, with fairly conclusive records of the "climatic optimum", of multiple Wisconsin glaciation, Sangoman interglacial, and Illinoian glacial stages, and by extrapolation, of Kansan and Nebraskan stges. (H.J.H.)

56/65—JOBBERNS, G.: Review of "New Zealand Geomorphology" by C. A. Cotton (1955). *N.Z. Geogr., 12 (1)* : 109-10.

A favourable review of this collected edition of Cotton's papers of 1912-1925 (abstract 55/18). Those who see no virtue in studies of the genesis of landforms are more likely to kill interest in geomorphology than stimulate it so powerfully as Cotton has done. (B.W.C.)

56/65—KAPLAN, I. R.: Evidence of Microbiological Activity in Some of the Geothermal Regions of New Zealand. *N.Z. J. Sci. Tech., B, 37 (6)* : 639-62, 5 figs.

A survey of the Rotorua-Taupo and White Island regions showed a very wide range of oxidation-reduction, pH, and thermal conditions. The acidity of certain pools may be partly due to the action of thiobacteria on sulphur, and these bacteria may also play a part in the formation of gypsum as at White Island. The role of algae in the deposition of travertine and siliceous sinter is discussed. A map of the White Island crater (after J. Healy) is presented. (From author's abstract.)

56/67—KING, C. A. M.: Recent Faulting in New Zealand. (Review of "New Zealand Quaternary Tectonics" by H. W. Wellman, 1955). *N.Z. Geogr., 12 (2)* : 209.

The New Zealand area, like California lying on the mobile circumpacific belt outside the andesite line and where two major structural units (the Pacific Ocean and the continental crust) meet, is a region of great importance in providing data for the interpretation of the activity of the earth's deep-seated forces. Wellman's division of the country into two outer zones of normal faulting and volcanic activity and an inner zone of transcurrent and reverse faulting is an alternative to the earlier "syntaxis" and "recurved arc" hypotheses. (B.W.C.) *See* 55/110.

LEED HEATHER: See Hil and Leed, 56/63; and Wood, 56/112.

56/68—LENSEN, G. J.; STEVENS, G. R.; WELLMAN, H. W.: The Earthquake Risk in the Wellington District. *N.Z. Sci. Rev., 14 (10)* : 131-5, 4 figs.

Relation of New Zealand to the Circum-Pacific Mobile Belt (Stevens, p. 131): The exact nature of the faulting (normal, reverse, or transcurrent) is known for only a few earthquakes.

Wellington District (Lensen, pp. 131-2): The West Tararua (Owhariu, Kakaho, Gibbs), Wellington, West Wairarapa, and East Wairarapa faults have been traced on air photographs and are considered to be essentially clockwise transcurrent faults. Horizontal displacement of terraces cut since the close of the last glaciation (10,000 years ago) amounts to as much as 310 ft at the Waiohine River on the West Wairarapa Fault. Displacements on a flight of terraces at Branch River, Marlborough, show that both river downcutting and transcurrent faulting have taken place at an essentially uniform rate since the last glaciation.

Earthquake Risk in the Wellington District (Wellman, pp. 132-5): Assuming that a major earthquake causes an average displacement of 10 ft over a trace 100 miles long, it is calculated from the known displacements on faults in the Wellington district over the last 10,000 years that there have been 130 severe earthquakes, or one per 80 years. Assuming a random distribution of earthquakes around the average, there is a 70% chance of a destructive earthquake at Wellington in 100 years and 45% chance in 50 years. (B.W.C.) *See also* Dibble, 56/40.

56/69—Lipson, J. I.: K–A Dating of Sediments. (Letter to the editors.) *Geochim. et cosmoch. Acta, 10 (1-2)* : 149-51, 2 figs.

The ages of nine samples of Tertiary glauconite from New Zealand and of three sedimentary minerals from Canada were determined from the ratios of radiogenic argon to potassium in the specimens. With few exceptions, probably due to contamination, the ages of the sedimentary minerals show good agreement with their stratigraphic arrangement. (B.W.C.) *See also* 56/70.

56/70—Lipson, J.: Potassium-Argon Dating of Sedimentary Rocks. (Abstract.) *Geol. Soc. Amer. Bull. 67 (12)* : 1818.

The University of California has developed techniques for dating samples of low radiogenic argon content. Results will include ages of series of glauconites from New Zealand ranging from Cretaceous (55 million years) to Miocene (20 million years). (C.A.F.) *See also* 56/69.

56/71—Lockerbie, L.: Moa Hunter Camps in Otago. *N.Z. geogr. Soc. Rec., 20* : 11-2.

Abstract of an address presenting the results of expeditions in 1954 and 1955 to the Catlins and Hawksbury districts. Material for radiocarbon dating was collected.

56/72—McKellar, I. C.: Geology of the Takahe Valley District, Eastern Murchison Mountains. *N.Z. J. Sci. Tech., B, 38 (2)* : 120-8, 6 figs. (incl. 2 geol. maps).

Rocks of the Fiordland Complex (granites and gneisses) in a small area between the South and Middle Fiords of Lake Te Anau are briefly described. Three formations in the Tertiary sequence (Point Burn Sandstone, Tunnel Burn Limestone, and Garden Point Formation) are defined. They appear to be only a basal remnant of a much thicker sequence. The glaciation of the valley, its post-glacial history, and the development of the present topography are outlined. (Author's abstract extended.)

McKellar, I. C.: *See also* Bell, Harrington, and McKellar, 56/12; Campbell and McKellar, 56/24; and Harrington and McKellar, 56/59.

56/73—McQueen, D. R.: Leaves of Middle and Upper Cretaceous Pteridophytes and Cycads from New Zealand. *Trans.roy. Soc. N.Z., 83 (4)* : 673-85, 3 figs.

Seventeen species are recorded from eleven localities, and the following new species described: *Sphenopteris mackayi, Cladophelbis wellmanii, Pterophyllum clarencianum, Ptilophyllum seymouricum.* The Paparoa Coal Measures, which had not previously been satisfactorily dated, contain plant fossils suggesting Senonian age. A figure shows the change in the composition of New Zealand Cretaceous floras so far known. The pteridophytes decreased in importance after the Neocomian and the cycads decreased in the later Cretaceous after a slight increase in the Turonian. Conifers increased during the Cretaceous. Angiosperms are first known about the Turonian and became dominant before the Senonian.

The known ranges of pteridophytes and cycads in the Cretaceous of Australia and New Zealand are summarized in a table. (Author's abstract extended.)

McQueen, D. R.: *See also* Wood, 56/112.

56/74—Marples, B. J.: Cetotheres (Cetacea) from the Oligocene of New Zealand. *Proc. zool. Soc. Lond. 126 (4)* : 565-80 (1956).

Three new species of Cetotheres, *Mauicetus lophocephalus, Mauicetus waitakiensis* and *Mauicetus brevicollis* are described from the Lower Oligocene (Duntroonian), of Duntroon, New Zealand. The greater part of the skull of one of these is present and it seems to be considerably the oldest Cetothere skull known. It appears to be primitive in that, although the supraoccipital shield extends as far forward as it does in many Miocene Cetotheres, the nostril is very anteriorly placed, the temporal fossae are longer than broad, and there is a long sagittal crest in the cranial region. There is, therefore, a considerable gap between the supraoccipital and the nasals, unlike the condition usually seen in the Mysticetes. A gap is present here in other early whales, but only in the Archaeocetes is it occupied by a sagittal crest. (Author's abstract.)

56/75—MARSDEN, E.: Hazards of Nuclear and Other Radiations. *N.Z. Sci. Rev. 14 (12)* : 155-62.

Includes tables giving details of the radioactivity of New Zealand soils and rocks. The radioactivity of greywacke is variable but fairly high. One hitherto unpublished area of high activity is the later Tertiary phonolites of the Dunedin district. (B.W.C.)

56/76—MARTIN, W. R. B.: Thorium-bearing minerals in New Zealanad. *Nature 178* : 1476.

Opaque-mineral sands in the Westport district contain 0.1% ThO_2, present in sphene and epidote-allanite. (H.J.H.)

56/77—MARWICK, J.: Three Fossil Mollusca from the Hokonui System (Triassic and Jurassic). *Trans. roy. Soc. N.Z., 83 (3)* : 489-91, 1 pl., 2 figs.

The Mid-Triassic fossil identified by O. Wilckens as *Pseudomonotis* ? sp. indet. is redescribed, figured, and named "*Chlamys*" *kakanuia*. The previously-missing holotype of the Upper Jurassic *Aulacosphinctoides sisyphi* (Hector) is figured. The species was based previously only on a crude wood-cut. Belemnite hooks from the Upper Jurassic of Kawhia are described and named *Onychites Maacnaughti*. (Author's abstract extended.)

MARWICK, J.: *See also* Wood, 56/113.

56/78—MASON, B. [H.]: Metamorphic Zones in the Southern Alps of New Zealand. *Amer. Mus. Novit., 1815.* 8 pp.

Criteria for field mapping of the greywackes and their metamorphosed equivalents, based on those established by Turner and Hutton for similar rocks in Otago, are as follows:

Chlorite 1: Unaltered greywacke.
Chlorite 2: Sheared greywacke.
Chlorite 3: Phyllonites, i.e., schistose and fissile rocks, not foliated.
Chlorite 4: Foliated schists without biotite.
Biotite : Presence of biotite.
Almandine: Presence of almandine garnet (and/or hornblende).

First applied in the district between the Franz Josef Glacier and the Copland Valley, this scheme has been shown by further work to be generally applicable in the Southern Alps between the Haast and Maruia Rivers. In a few places, especially north of the Taramaku Rivers, some difficulty has been caused by the absence of a Chlorite 4 zone, Chlorite 3 rocks passing directly into Biotite zone rocks.

Subsequent laboratory examination showed that the Almandine zone could be divided into two district zones—one in which the felspar is albite and one of higher grade in which it is more calcic (oligoclase–andesine).

The "foliated mica schists" of Wellman, Grindley, and Munden (1952) fall entirely within the Biotite zone, as do also their "non-foliated mica schist" and part of their "lower sub-schist". The remainder of the "lower sub-schist" is probably equivalent to the Chlorite 3 zone, the "middle sub-schist" to the Chlorite 2 zone, and the "upper sub-schist" to the Chlorite 1 zone.

A table shows the relationship of the metamorphic zones recognized by Mason to the facies classification of Turner and and Verhoogen (1951). Brief notes on the following individual minerals are given: quartz, clacite, muscovite, chlorite, biotite, felspar, tremolite-actionlite, hornblende, garnet, and clinozoisite-enstatite.

The only mineral specific to a single zone is oligoclase or andesine. A rock may belong to the Almandine zone, yet its composition may be such that garnet will not form. On the whole, however, the application of zonal criteria on a regional scale is feasible. Mapping in the central and northern parts of the Alps is expedited by the simplicity of structure, the grade of metamorphism increasing uniformly from the Main Divide westward. South of the Copland Valley, however, post-metamorphism folding has caused repetition of some zones.

The highest grade of metamorphism reached is that of the Oligoclase zone. Absence of higher grade minerals such as sillimanite and wollastonite implies that temperatures exceeding 500-600° C were never attained. (B.W.C.)

56/79—Moody, J. D.; Hill, M. J.: Wrench-Fault Tectonics. *Geol. Soc. Amer. Bull., 67 (9)* : 1207-46, 25 figs.

Extension of the work of Anderson, Hubbert, and Hafner on faulting leads to the conclusion that for any given tectonic area, at least eight directions of wrench (lateral, transcurrent) faulting and four directions of anticlinal folding and/or thrusting should accommodate the structural elements. The authors' interpretations indicate that wrench-fault tectonic systems do exist anad are aligned systematically over large portions of the earth's crust, as suggested by Hobbs, Vening, Meinesz, Sonder, and others. Eight principal wrench directions are defined in terms of major elements of the earth's crust such as the Alpine Fault of New Zealand. Structural elements aligned in these eight directions constitute major features of the regmatic shear pattern of Sonder. The authors conclude that the shear pattern may have resulted from stresses oriented essentially meridionally and acting in nearly the same direction throughout much of crustal history.

Possible origins of the stresses, formation of island arcs, volcanism, and crustal evolution are discussed. (B.W.C. from authors' abstract.)

56/80—Odell, N. E.: Air Survey of the New Zealand Alps. *Geogr. J., 122(4)* : 451-5, 6 pls.

Description of flights along east and west sides of Southern Alps from Harper Pass to Mt Earnslaw, with eight oblique aerial photographs. The Douglas Glacier shows a large amount of recent recession. Conspicuous blocks of moderately dipping strata form many Main Divide peaks, especially south of Mt Whitcombe. Isoclinal and even local recumbent folds are mentioned and indicated in photographs. (B.W.C.)

Nicholson, D. S.: *See* Billinghurst and Nicholson, 56/14.

56/81—Odell, N. E.: So-called "Glacier-Worms" in New Zealand. (Letter to editor). *Nature, 177 (4507)* : 534.

Tiny "worms" occurring in ice and melt-water pools and streams on Franz Josef Glacier were first reported by Charles Douglas, and have been identified as larvae and pupae of a chironomid fly. (H.J.H.)

56/82—Oliver, R. L.: The Origin of Garnets in the Borrowdale Volcanic Series and Associated Rocks, English Lake District. *Geol. Mag., 93 (2)* : 121-39, 1 pl., 5 figs.

Includes (p. 135, footnote) brief reference to the occurrence in New Zealand of garnets in rocks with 69·54 and 75·68 per cent. silica, in contrast to their restriction elsewhere to rocks whose silica percentage ranges from 59 to 70. (B.W.C.)

56/83—Oliver, W. R. B.: The Genus *Aciphylla. Trans. roy. Soc. N.Z., 84 (1)* : 1-18, 8 pls.

In this monograph on a genus of New Zealand plants it is mentioned (p. 2) that Hector's *Aciphylla pungens* from early Tertiary strata at Wangapeka looks much more like a spine of *Discaria*. (B.W.C.)

56/84—OLSON, O. P.: The Genus *Baryspira* (Mollusca) in New Zealand. *N.Z. geol. Surv. pal. Bull. 24.* 32 pp., 7 pls., 7figs.

The New Zealand species of the gastropod genus *Baryspira* (Olividae) are revised. Thirty-three species, three sub-species, and one variety are distinguished and figured! Three sub-genera are proposed, twelve species, one sub-species, and one variety introduced, two species' names become synonyms, and two become sub-species names. One species of doubtful position (probably an *Ancilla*) is described in an appendix. The genus is not known before the Tertiary. There is one Eocene species, nine in the Oligocene, fourteen and one variety in the Miocene, eleven in the Pliocene, seven in the Pleistocene, and five species now living in New Zealand. Many of the species have restricted time-ranges. (Author's abstract, extended by C.A.F.)

56/85—POWNALL, L. L.: Groundwater in New Zealand. [Review of two papers by B. W. Collins.] *N.Z. Geogr., 12 (2)* : 198-9.

A review and summary of parts of interest to geographers of articles in the Report of the International Association of Hydrology (Rome Assembly, 1954). *See* 55/15 and 16.

REILLY, W. I.: *See* Evison and Reilly, 56/44.

ROGERS, J.: *See* Buckenham, Rogers, and White, 56/21.

56/86—SCHOFIELD, J. C.: Methods of Distinguishing Sea-Ground-Water from Hydro-thermal Water. *N.Z. J. Sci. Tech., B, 37 (5)* : 597-602.

The term "sea-ground-water" is used for a mixture of sea-water and normal ground water. Such mixtures are similar in composition to alkaline hydrothermal waters. A discussion of the chloride/bromide and chloride/magnesium ratios leads to the conclusion that these are of value in distinguishing the two types of waters. The chloride/magnesium ratio is generally higher for alkaline hydrothermal waters than for sea-ground-water. The ionic changes that occur in sea-water that is in contact with sediments are also discussed briefly. (Author's abstract modified.)

56/87—SCHOFIELD, J. C.: Ground Water in the Waikato. *N.Z. J. Agric., 93 (1) (July)* : 67, 69-71, 73, 75, 10 figs.

Ground water is the principal source of farm and domestic water supplies in the Waikato area of the North Island. With the growth of spray irrigation it will become increasingly important. The quantity and quality of the ground water are related to the sediments (greywacke, limestone, papa, sandstone, soft sands, and pumiceous silts) from which it is obtained. Different sediments are associated with different topographic reliefs, and a guide is given to enable the farmer to tell the type of sediment underlying his farm and hence the amount and quality of the water he is likely to obtain by drilling.

The origin, occurrence, and movement of ground water are briefly discussed, and also the likely effects of irrigation on the water table. Some of the Pleistocene sediments (Hamilton and Hinuera Formations) contain water with a high iron content, owing to the occurrence of buried peat layers. (Author's abstract extended.)

56/88—SEARLE, E. J.: Aspects of the Pleistocene and Recent History of the Auckland Isthmus. *N.Z. Geog. 12 (1)* : 75-88, 5 figs.

Since the Auckland area suffered little tectonic disturbance during the Pleistocene its geological history has been dominated by the world-wide oscillations of sea-level due to fluctuations in the intensity of glaciation. Five groups of erosion levels have been recognized on the Auckland isthmus. Volcanic activity began during the later stages of the post-glacial sea-transgression, and phreatic, explosive, and non-paroxysmal eruptions are briefly discussed. Reconstruction of the pre-volcanic surface configuration of the area are shown in maps based on drilling records and other considerations. The volcanic history and probable sequence of eruptions of the Manukau area are discussed in detail. Ground water occurs abundantly in joints and caverns in the basalt flows. (B.W.C.)

56/89—SHARP, R. W.: Cossey's Dam. Auckland Water Supply Development. *Commonw. Engr., 43 (7)* : 223-9, 4 figs.

Includes (p. 224) a short account of geological investigations of the site of a rolled-earth dam, in the Hunua ranges. The weathering profile on a greywacke-argillite complex is important for locating borrow pits, and because weathered material is less permeable than fresh. An abandoned infilled valley of Cossey's creek is mentioned. (H.J.H.)

56/90—S[IEMON], S. R.: Chemicals and Metals from South Island Mineral Resources. *Caanterbury Chamb. Comm. Econ. Bull. 380.* 4 pp.

Resources known to be present in large quantities include coal, sea-salts, clay, sand, limestone, and dolomite, and iron-sands. Magnesium carbonate for heat insulation could be manufactured from dolomite and sea-water; calcium carbide, calcium cyanamide, and P.V.C., from limestone, coke, and hydroelectricity; ceramics, glass, and cement from abundant raw materials; aluminium, iron, and titanium (metal and dioxide) are also possibilities. (B.W.C.)

56/91—SQUIRES, D. F.: Climatic Interpretation of Cenozoic Faunal Migrations in New Zealand. *Trans. N.Y. Acad. Sci. ser. 2, 18 (5)* : 415-26.

Summarizes work on the present oceanographic position of New Zealand and on the movements of Cenozoic marine faunas (forminifera, corals, and molluscas). The author includes a summary of the paleoclimatic interpretation of his work on New Zealand fossil corals, illustrated by diagrams showing the distribution of coral genera in the middle Eocene, middle Oligocene, and lower Miocene. (C.A.F.)

56/92—STEVENS, G. R.: Hutt Valley Artesian System. *N.Z. J. Sci. Tech., B, 38 (3)* : 149-56, 4 figs.

The alluvial filling of the Lower Hutt-Port Nicholson Basin, designated the Hutt Formation, contains a prominent aquifer, the Waiwhetu Artesian Gravels, overlain by impervious silts and clays. These gravels extend from just north of Hutt City to about two miles south of Somes Island, and constitute the Hutt Valley artesian system. The primary source of supply is thought to be the Hutt River, 30 million gallons a day (of a minimum total flow of 50 m.g.d.) going underground at the intake point. Rainfall is of secondary importance. (From author's abstract.)

56/93—STEVENS, G. R.: Stratigraphy of the Hutt Valley, New Zealand, *N.Z. J. Sci. Tech., B, 38 (3)* : 201-35, 15 figs.

The strata include basement greywackes (Rimutaka Group), high-level gravels (Haywards Gravels), and the alluvial Hutt and Trentham Formations, filling the Lower Hutt-Port Nicholson and Upper Hutt Basins respectively.

On the rocks of the Rimutaka Group there was developed in Late Tertiary times an erosion surface (Kaukau Surface) bearing a deeply-weathered and in some places red-stained regolith. Transcurrent faults dislocating this surface in Early-Middle Pleistocene caused widespread intense shattering of the Rimutaka Group. The Haywards Gravels, also dislocated, are terrace remnants more than 42,000 years old, formed on a former flood-plain of the Hutt River. To the east of the Wellington Fault they are down thrown and buried by the Hutt Formation, while to the west the terrace remnants have been modified by solifluxion.

The Trentham Formation consists of a lower lacustrine member (100 ft thick) and a fluviatile member (50 ft). The Hutt Formation, approximately coeval, is sub-divided into: (1) Moera Basal Gravels; (2) Wilford Shell Bed (4 ft), marking the incursion of the Flandrian sea; (3) Waiwhetu Artesian Gravels (200 ft), deltaic deposits of Flandrian age, 7-11,000 years B.P.; (4) Petone Marine Beds (20 ft), marine silts and clays marking a sudden transgression at the beginning of the post-glacial Thermal Maximum period, about 6000-7000 years B.P.; (5) Melling Peat (3 to 6 ft), deposited 4250 years B.P.; and (6) Taita Alluvium (40 ft), the fluviatile veneer of the Hutt delta. (From author's abstract.)

56/94—STEVENS, G. R.: Earth Movements in the Wellington Area. *N.Z. Geogr., 12 (2)* : 189-94, 5 figs.

Two uplifts have occurried within historic time: a pre-1840 uplift of about four feet, and the uplift of five feet at the time of the Wellington earthquake of 1855. The pre-1840 uplift is probably the earth movement that assisted the formation of the sand isthmus that now ties the former Miramar Island to the mainland, and its date was probably between 1400 and 1700 A.D. (From author's conclusion.)

STEVENS, G. R.: *See also* Lensen, Stevens, and Wellman, 56/68.

56/93—SUGGATE, R. P.: Pupoga Coalfield. *N.Z. J. Sci. Tech., B, 37 (5)* : 539-59, 2 figs. (incl. geol. map).

The stratigraphy and structure of Puponga Coalfield, in the extreme north-west of the South Island, New Zealand, are deduced from mining, drilling, and field observations. The Pakawau Group of coal measures is subdivided into four formations (North Cape, Puponga, Wharariki, and Farewell), and the age—late Cretaceous to Eocene—is discussed. The greater part of the coal has been won from one seam. Mining has produced 550,000 tons, and a further 300,000 tons is estimated to be recoverable from the abandoned workings and adjacent areas. The coal is of high-volatile B bituminous rank (A.S.T.M. classification) and has a low sulphur content. (From author's abstract.)

56/96—SUGGATE, R. P.: Air-drying of Coal. *N.Z. J. Tech., B, 38 (3)* : 139-48, 5 figs. (graphs).

Six coals, ranging in rank from lignite with 54% moisture to bituminous with 5%, were air-dried. Equilibrium moisture contents for relative humidities ranging from 52% to 86% were estimated. It is inferred that there is a progressive decrease in average pore size in coal with increasing rank. Standardization of conditions for air-drying and the determination of natural bed moisture are required. In the meantime classification of New Zealand coals should be on the "dry" basis. (From author's abstract.)

56/97—SUGGATE, R. P.: Depth-Volatile Relations in Coalfields. *Geol. Mag., 93 (3)* : 201-17, 4 figs. (graphs).

New evidence from the Greymouth Coalfield, New Zealand, is presented, and the British evidence reviewed. A maximum rate of downward decrease of volatiles is inferred at 23% volatiles, and a depth-volatile band from 42% to 5% volatiles is presented. British coalfield sequences fit this band, rendering unnecessary the complex geological explanations for differing rates of downward decrease of volatiles given by previous authors. Tectonic pressure as a cause of rank differences is rejected in favour of depth of burial. (From author's abstract.)

56/98—SUGGATE, R. P.: New Zealand Coals. (Letter to Editor.) *Nature, 178 (4536)* :, 757, 2 figs. (graphs).

New Zealand coals, mainly of early Senonian to early Oligocene age, belong to a restricted range of coal type, different from that of British and North American coals of Carboniferous age. The mean line for the New Zealand coal band agrees better with that of Mott, than with those of Francis and Seyler. (B.W.C.)

SUGGATE, R. P.: *See also* Dibble and Suggate, 56/41.

56/99—TAYLOR, S. R.; EMELEUS, C. H.; EXLEY, C. S.: Some Anomalous K/Rb Ratios in Igneous Rocks and their Petrological Significance. *Geochem. et Cosmoch. Acta 10* : 224-9.

Includes data on the K/Rb ratios for basalts, andesites, and rhyolites from Bank's Peninsula. The rhyolites are relatively enriched in Rb, and must have crystallized from extremely differentiated magma which contained notably little Ba, Sr, and Zr, as compared with average granite. (H.J.H.)

56/100—TE PUNGA, M. T.: Fossil Ice-Wedges near Wellington. *N.Z. J. Sci. Tech.*, *B, 38 (2)* : 97-102, 1 fig.

Features at Kaitoke, near Wellington, are described and interpreted as fossil ice-wedges, thus indicating perennially frozen ground. Their method of formation is discussed. Brief reference is made to two other ground-ice features—fossil ice lenses and honeycomb structure. (Author's abstract modified.)

TRICART, J.: *See* Cotton and Tricart, 56/33.

56/101—UTTLEY, G. H.: Remarks on the Bryozoan Genera *Spiroporina Stoliczka* and *Haswellina* Livingstone and their Genotypes. *Trans. roy. Soc. N.Z.*, *84 (1)* : 29-31.

The view that the genotypes of *Spiroporina* Stoliczka 1865 and *Haswellina* Livingstone 1928 are conspecific is shown to be erroneous. It is maintained that these genotypes belong to different families. *Spiroporina* is shown to be a synonym of *Porina* d'Orbigny 1852, and must lapse. *Haswellina* is reinstated as a valid genus. Revised synonymies and diagnoses of the genera are given. (From author's abstract.)

56/102—VAN'T WOUDT, B. D.: Observations on the Efficiency of Sub-Irrigation in Heavy Soils. *Trans. Amer. geophys. Un.*, *37 (5)* : 588-92, 1 figs.

Experimental work at Rukuhia with various depths of water table showed that sub-irrigation can be quite successful if supplemented by rain. (B.W.C.)

WALKER, I. K.: *See* Fieldes, Walker, and Williams, 56/47.

WALLACE, W. H.: *See* Cotton, Baulig, and Wallace, 56/32.

56/103—WATERHOUSE, J. B.: Recent French Contributions to the Geology of New Caledonia. *N.Z. J. Sci. Tech., B, 37 (5)* : 587-96, 1 fig., table.

Recent publications, especially by Avias, Pomeyrol, and Routhier, are summarized, with particular reference to the similarities and contrasts to New Zealand stratigraphy and to theories on the origin of serpentine. Key fossils (including *Maitaia, Mytilus, Monotis,* etc.) are listed. (B.W.C.)

56/104—WATSON, W. B.: New Zealand's Coal Resources. *N.Z. geogr. Soc. Rec.*, *20* : 7-8.

An abstract of an address reviewing the production and prospects of the coal industry.

56/105—WEBSTER, K. A.: Jade or Greenstone. . . . Which? (Note). *J. Polynes. Soc., 65 (2)* : 174, 176.

In the interests of uniformity throughout the world it is suggested that New Zealanders should use the term "jade" rather than "greenstone", especially in descriptions of artifacts of nephrite. It is admitted that "jade" covers both nephrite and jadeite, and that there is none of the latter in New Zealand. The term "greenstone" is confusing as it covers both nephrite and bowenite. (B.W.C.) *See also* Adkin, 56/2.

56/106—WELLMAN, H. W.: Structural Outline of New Zealand. *N.Z. Dep. sci. industr. Res. Bull 121.* 36 pp., 5 folding maps.

A brief but fairly comprehensive review of present knowledge of the structure and stratigraphy of New Zealand by regions (pp. 7-22) and by periods (pp. 22-30) is followed by a summary and a bibliography of 151 items. Maps, in a pocket inside the back cover, show: structural regions; distribution of pre-Cretaceous rocks of the South Island; Mesozoic structures, and some inferred paleogeographic boundaries; late Tertiary and early Quaternary volcanic rocks, major anticlines, and faults; and main active faults, late Quaternary and active volcanoes, and submarine contours at 500 fathom intervals.

The author emphasizes that the geological history of New Zealand has been dominated by continuing and intense tectonic activity contrasting with that of most of the continental parts of the world. As deformation proceeded, the pattern of land and sea changed, the rocks being compressed in some places and extended in others, and everywhere tilted either slowly or rapidly. This shows now as folds or faults, or by the gradual thickening of beds of a particular age. Volcanoes appeared at times but all except those of the last million years are worn away and only their products remain.

Except for a brief period at the end of the Cretaceous there has always been considerable land and submarine relief, which is reflected in the sediments deposited. Until the mid-Cretaceous they were mostly thick, dark, felspathic sandstones—the New Zealand greywackes—implying mountains with volcanoes, fast rivers, and quick transport to rapidly subsiding marine trenches. The change to the quartzose and bentonitic sediments of the uppermost Cretaceous and lower Tertiary suggests that the mountains were worn down and the trenches filled in. The later Tertiary sediments are more like those being deposited off the New Zealand coast today, and conditions were like those of the present.

Two features of the geological history seem well established and important. The first is that uplift and sedimentation were complementary. While some parts of the New Zealand area were rising, other parts were sinking and accumulating sediments. The tempo varied from place to place and from time to time, but the average rate was probably not very different from that of the present day. The pattern of sedimentation changed significantly at several different periods. The earliest known is the Devonian, when probably the New Zealand Geosyncline was initiated. The next is the middle Jurassic, when this geosyncline began to evert, and upper Mesozoic geosynclines formed to the east. Then, at the end of the Cretaceous, the tempo of deformation slowed down over most of New Zealand, and the sea transgressed west to new but smaller basins of deposition. The next change was in the mid-Tertiary—the beginning of the growth of the mountains we see today and possibly the beginning of the submarine trench to the east.

The other feature is the formation of new geosynclines on the Pacific Ocean side of the older ones. The position of the Lower Paleozoic Geosyncline is not well established but it was probably on the west side of the present land area. The New Zealand Geosyncline roughly corresponds to the present land area. Except in western Northland the Upper Mesozoic geosynclines are to the east. The present-day geosyncline—the Kermadec-Tonga submarine trench—is still farther to the east. (B.W.C.)

56/107—WELLMAN, H. W.: The Cretaceous of New Zealand. *XX Congr. Geol. Int., Mexico. Resumenes de los Trabajos Presentados*, pp. 351-2, table.

The proposed divisions of the New Zealand Cretaceous and the more important fossils are set out in a chart. Undescribed key species of *Inoceramus* are indicated by letters and related European forms given. In downward succession, new stages are: Haumurian (below Teurian) in the Mata Series; Teratan, Mangaotanean, and Arowhanan in the Raukumara Series; Ngaterian, Motuan, and Urutawan in the Clarence Series; and Coverian (above Taitai Sandstone and Mokoiwi Mudstone) in the new Urewera Series. Haumurian is correlated with Maestrichtian, Raukumara Series with Santonian-Coniacian, Ngaterian and Motuan with Turonian, Urutawan with Cenomanian, Coverian with Albian, and underlying parts of the Urewera Series with Aptian-Neocomian. (C.A.F.)

WELLMAN, W. H.: *See also* Lensen, Stevens, and Wellman, 56/68.

WHITE, C. C.: *See* Buckenham, Rogers, and White, 56/21.

56/108—WHITLEY, G. P.: New Fishes from Australia and New Zealand. *Proc. Roy. zool. Soc. N.S.W., 1954-55* : 34-8, 2 figs.

The new specific name *kaikorai* is proposed (p. 34) for the fossil *Galazias* from diatomaceous shale of probably late Pliocene age, Kaikorai, near Dunedin. The topotype, described by Stokell (*Trans. Roy. Soc. N.Z., 75* : 134-6, pls. 11, 12), is in the geological museum of Otago University. (B.W.C.)

WILLIAMS, P. P.: *See* Fieldes, Walker, and Williams, 56/47.

56/109—WILSON, D. D.: Note on the Geology of the Ant Stream Tertiary Outlier, North Canterbury, New Zealand. *N.Z. J. Sci. Tech., B, 37 (5)* : 603-5. 1 fig.

An outlier of Tertiary rocks in the basin of the Waimakariri River about 20 miles from the Main Divide is described. A Southland (early Miocene) age is established for part of the section and also for fossiliferous boulders previously considered Pareoran (late Oligocene). (From author's abstract.)

56/110—WILSON, D. D.: The Late Cretaceous and Early Tertiary Transgression in South Island, New Zealand. *N.Z. J. Sci. Tech., B, 37 (5)* : 610-22, 1 fig. (map).

The ages of basal marine members of late Cretaceous and early Tertiary sequences throughout the South Island are shown on a map, and the lithology of the sections given in a table. Sub-division is made into the following series: Mata (Campanian-Danian), Dannevirke (lower Eocene), Arnold (upper Eocene), and Landon (lower Oligocene). The pattern suggests that progressive marine transgression towards the present Alpine divide (from both west and east) began in the Cretaceous and culminated in the Oligocene with widespread submergence. (Author's abstract slightly modified.)

56/111—WOOD, B. L.: The Geology of the Gore Subdivision. *N.Z. geol. Surv. Bull. 53.* 128 pp., 46 figs., geol. maps.

The oldest rocks occur in the north-east part of the subdivision and consist of siliceous greenish greywacke and interbedded dark shale and phyllite. They are termed Tuapeka Group and are possibly of Carboniferous age. Greywacke, tuffaceous greywacke, interbedded mudstone, and rare conglomerates and limestones stratigraphically above the Tuapeka Group are divided into the Waipahi (older) and Arthurton (younger) groups. Sodic volcanic rocks are interbedded in the Waipahi Group and are associated with small intrusions. The Arthurton Group and at least part of the Waiapahi Group are Permian.

Mesozoic rocks occur in the southern part of the subdivision and consist of well-bedded dominantly tuffaceous sandstones and mudstones with interbedded conglomerates. Plant remains are found in the lower part of the Triassic sequence and in the two higher groups of the Jurassic beds. Marine fossils (mollusca, brachiopoda) occur in the middle and upper parts of the Triassic and in the lower part of the Jurassic sequences.

Tertiary beds crop out in the central and north-west parts of the area and constitute a relatively thin unconformable cover overlying a leached peneplain surface cut in the older rocks. The Oligocene strata consist of kaolinitic clay, quartz sand, lignite, carbonaceous mud and silt, shelly sand, and gypsiferous mud. Pliocene deposits are of two types—white quartz conglomerates and sands, and coarse greywacke and schist gravels with a rusty-brown clay matrix.

Pleistocene and Recent alluvial deposits occupy many of the low-lying areas and the terraced margins of the larger valleys. A thin cover of loess-like material mantles some of the more gentle slopes.

The pre-Tertiary strata form part of the steeply-dipping north-east limb of the major Southland Syncline. In the Waipahi district thrusting from the north-east has overturned and folded the strata. It is probable that in the early Tertiary the area was a land of low relief, subject to subaerial erosion for a greater part of the time. During the middle Tertiary a thin cover of estuarine and fluviatile deposits was laid down and there was a brief marine transgression.

In the later Tertiary non-marine quartz conglomerates and sands were deposited slowly; but in the late Pliocene accelerating earth movements of the

Kaikoura Orogeny elevated some areas, and the intervening depressions were infilled with terrestrial quartz-greywacke gravels. Broad piedmont plains were formed in the early Pleistocene. Subsequently, faulting and gentle warping along north-north-east axes initiated the main features of the present drainage system. Gentle cross-warping along north-west axes followed, resulting in the many antecedent reaches of the present streams. Terraces have been cut indiscriminately on indurated greywackes and igneous rocks, and on soft Tertiary muds, sands, and gravels.

Economically the most important deposit is lignite, which has been mined for many years. Kaolin clays of several qualities are known but have not yet been used in the ceramic industry. Loess-like silty clays are used in the manufacture of bricks. A small quantity of clean wind-blown quartz sand is available, and there is a small deposit of limestone. Road-metal and gravel are plentiful.

The bulletin includes as an Appendix (pp. 120-3) a report on plastic clays in the subdivision by the New Zealand Pottery and Ceramics Research Association, and is accompanied by a coloured dissected block diagram and a coloured geological map on the scale of one inch to one mile .

Identifications of Mesozoic and Tertiary macrofossils by J. Marwick and Heather Leed, of Tertiary microfossils by N. de B. Hornibrook, and of plant remains by R. A. Couper, D. R. McQueen, and S. Bell are incorporated in the text, together with petrographic descriptions by J. W. Harris. (B.W.C.)

56/112—YALDWYN, J. C.: A Preliminary Account of the Sub-Fossil Avifauna of the Martinborough Caves. *Rec. Dom. Mus.* [*N.Z.*], *3 (1)* : 1-7.

Reports the finding of remains of moa, kiwi, takahe, kakapo, kaka, etc., during excavations in 1920 and 1952. (B.W.C.)